ARMY RESEARCH LABORATORY

Modal Analysis of the Prototype Heavy Composite Hull (HCH)

by Morris Berman

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Modal Analysis of the Prototype Heavy Composite Hull (HCH)

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Abstract

A modal analysis was performed on the heavy composite hull (HCH). The object of this experiment was to provide structural dynamic information to be used to validate a finite element model. The experimental model was also used to update the finite element model, as well as to provide damping information.

This report details the analysis performed on the HCH in two configuration. The first configuration utilized excitation by four shakers placed at the corners of the floor. The second configuration also utilized four shakers, but two were placed on the roof in an attempt to excite local modes.

The first elastic mode of the HCH was observed at 36.1 Hz (0.425% critical damping). Modes up to 100 Hz were analyzed for this report. This report describes the characteristics of the extracted modes.

Acknowledgments

The author of this report wishes to acknowledge the assistance of Jason Blough and Susan Dumbacher of the University of Cincinnati in the experimental aspects of this report. The author would also like to thank Dr. Stuart Shelley for his assistance in the analysis portion of this project. The Nuclear and Directed Energy Division of the Weapons Technology Directorate (WTD) provided the use of the High-Power Microwave (HPM) facility so that the test could be performed at the Adelphi Laboratory Center (ALC) in an environmental controlled, noise-free enclosure.

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Table of Contents

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List of Figures

Figure		Page

Figure		Page

List of Tables

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1. Introduction

A modal test and analysis were performed on the heavy composite hull (HCH) by the Mechanics and Structures Branch (MSB) of the U.S. Army Research Laboratory (ARL). The results of the analysis will be utilized by the Terminal Effects Division (TED) of ARL for the validation of finite element (FE) models. These models will be used to assess the vehicle's survivability under munitions blast effects and nonperforating impact from projectiles.

The modal test was carried out with the assistance of the University of Cincinnati, Structural Dynamics Research Laboratory (UC/SDRL) under contract to MSB. The UC/SDRL personnel directed the modal test. UC/SDRL also provided a significant portion of the test instrumentation, resulting in a significant cost savings to the government. After the conclusion of the test, UC/SDRL performed a preliminary analysis to verify the data integrity.

The UC/SDRL report [1] and the data integrity checks, as well as the final data set, were transferred to MSB for the complete analysis. This report presents the results of the complete modal analysis performed by MSB.

The HCH is the third vehicle on which the MSB has performed a modal analysis. Therefore, this report does not detail the general aspects of modal analysis. The reader is directed to Berman and Li [2]; Berman [3]; Braun [4]; and Brown, Allemang, and Zimmerman [5], which include sections that further explain the details of modal analysis.

This test differed from the previous two tests in that an *a priori* analytical modal analysis had been performed on the FE model. This information provided insight into the optimal locations of the modal exciters.

2. Modal Test Configurations

2.1 Vehicle Description. Unlike previous vehicle tests, only a single vehicle configuration was available for testing. That configuration consisted of the bare HCH (Figure 1). When tested, the hull had not been fitted with an engine/transmission, turret, seats, controls, or any other component of any size. The vehicle is approximately 28 ft × 11 ft × 6.5 ft and weighed approximately 27,000 lb. The hull can be identified by POT no. 4231863.

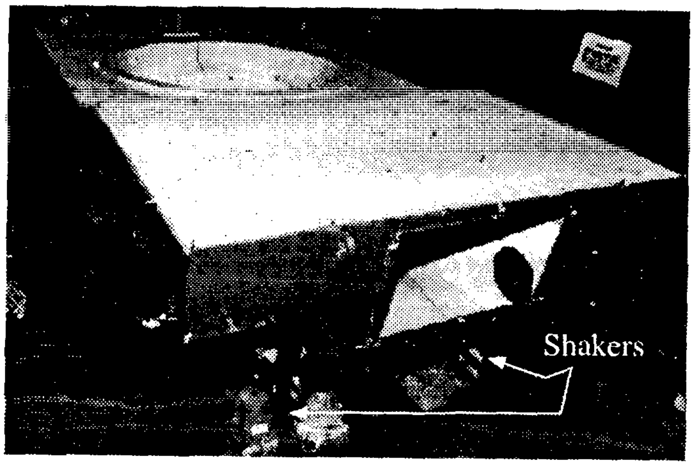

Figure 1. Overall View of HCH.

2.2 Excitation and Data Acquisition System. The data acquisition system consisted of an Hewlett-Packard (HP) Unix workstation running the I-DEAS Test Software Suite coupled to a 128-channel HP 3565 series data acquisition front end. Four MB Dynamics Modal 50 shakers were utilized to excite the structure, and PCB model 336 accelerometers were used for the response measurements. The vehicle was instrumented at approximately 240 response nodes in three orthogonal directions. Due to a limited number of input channels, the data acquisition system was only patched into 120 response node accelerometers at a time. This technique resulted in six acquisition cycles (three directions at each of two locations).

The exciters are rated at 50-lb force with forced air cooling and 25 lb without. This test did not utilize forced air cooling of the shakers. Each shaker location was instrumented with a PCB force transducer, as well as its own accelerometer. The set of driving point transducers was measured for every data set that was taken. In addition, these sets of transducers provided the driving point measurements. A typical excitation location appears in Figure 2, and a typical response point appears in Figure 3. (The triax block permits the sensor to be rotated so that X, Y and Z responses can be measured). The shaker was attached to the vehicle/force transducer via a narrow stinger. The stinger significantly reduces moments that might be transmitted from the shaker to the vehicle due to small misalignments.

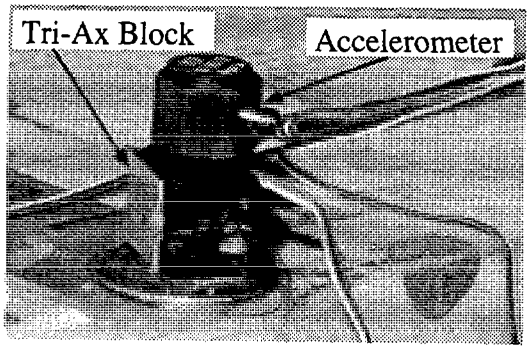

Figure 2. Typical Response Point.

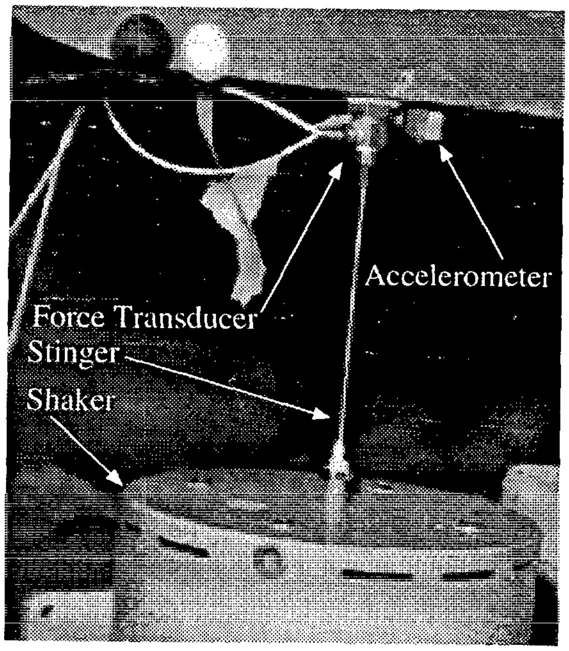

Figure 3. Typical Excitation Location.

The frequency response functions (FRFs) were computed using the H1 method of estimation. Burst random excitation was chosen to reduce leakage errors. The FRFs were obtained for two frequency ranges (0–100 Hz and 100–200 Hz) with a 2,048-point frame size; 100 averages were used to estimate the FRFs. The FRF estimation was done in two frequency ranges to increase the amount of energy available at each frequency range.

2.3 Test Setup. The vehicle was suspended on a set of four Firestone model 113 Airride supports (the specifications are found in Appendix A). If the frequency interval between the last rigid-body mode and the first flexible mode is sufficiently large, the structure can be assumed to have free-free boundary conditions. The highest frequency rigid-body mode of the HCH is less than 3 Hz, and the lowest frequency flexible hull mode is greater than 30 Hz. The ratio of 10 (30:3) between these two modes is sufficient to neglect any interaction between the flexible modes and the rigid-body modes.

Two test configurations were utilized. Configuration 1 consisted of four shakers located at the four corners of the floor of the hull (Figure 1). The locations were chosen to excite the global modes of the chassis. This shaker configuration has been used on each of the previous vehicle tests with excellent results. A second shaker configuration was also tested based on input from the FE modeler.

The second shaker configuration was primarily intended to better excite the panel modes of the HCH structure. This configuration also utilized four shakers. The two shakers exciting the left side of the floor remained there. The other two shakers were suspended above the hull to excite the roof (Figure 4).

2.4 Modal Model. The node locations were chosen to provide an adequate geometric description of the mode shapes; therefore, the response degrees of freedom (DOFs) were evenly distributed throughout the hull and empty turret basket. The computer geometry for the modal model appears in Figure 5. This geometry will be made available in electronic format along with extracted mode shapes and modal parameters.*

* The electronic addendum can be obtained by e-mailing a request to the author (mberman@arl.mil).

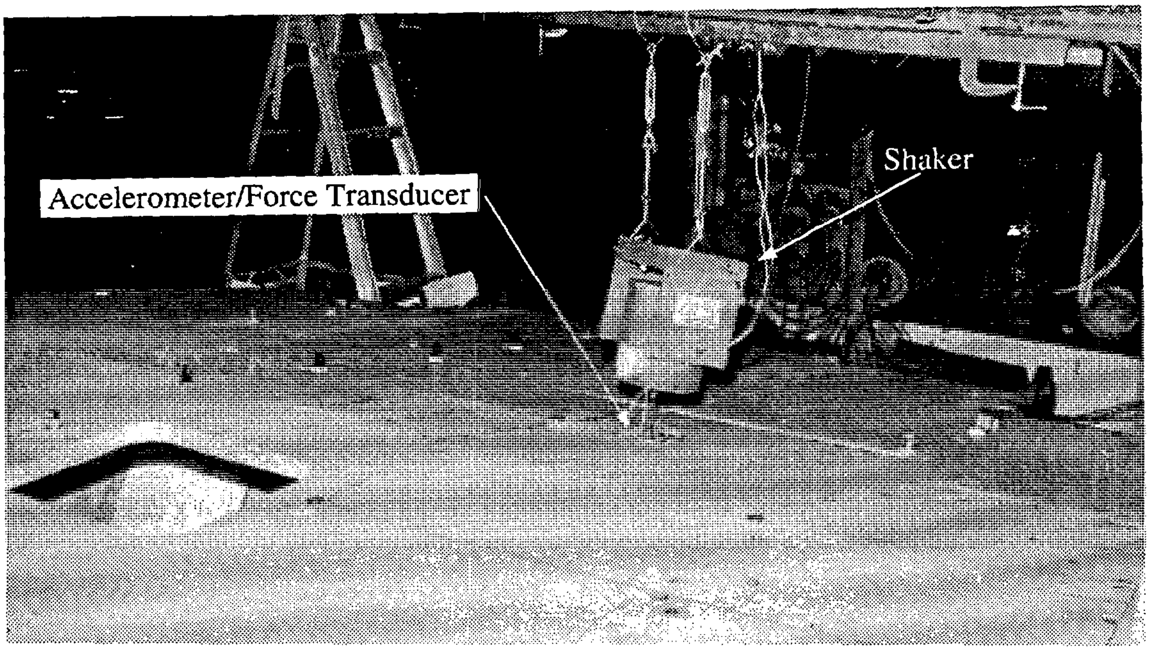

Figure 4. Roof Shaker Suspension.

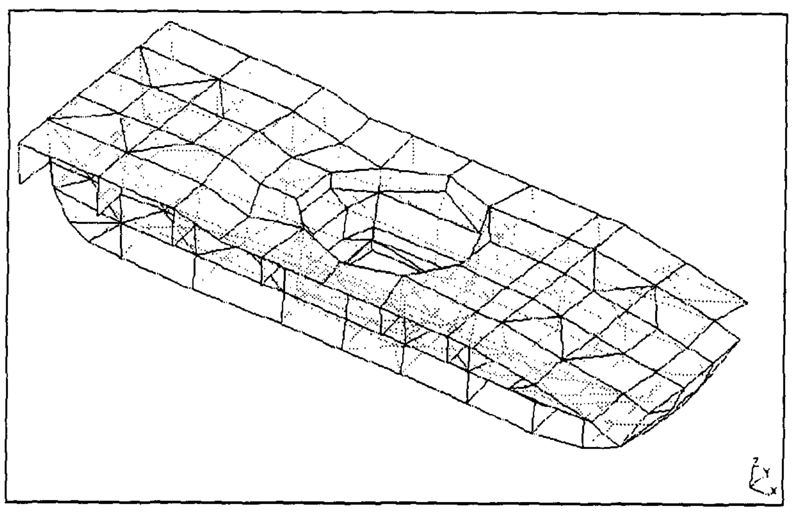

Figure 5. Modal Model Geometry.

3. Modal Analysis Results

3.1 General Description. All parameter extraction and analysis was performed on an HP workstation utilizing SDRC's I-DEAS modal analysis software. All parameter extraction and mode shape curve-fitting was accomplished using the polyreference curve-fitting technique.

Due to the complexity and number of extracted mode shapes, this paper does not attempt to describe each shape individually. Instead, it describes the generalized characteristics of the observed mode shapes, and printouts of the mode shape are provided in Appendices A and B. In addition to these brief descriptions, the mode shapes will be made available electronically in conjunction with a short Matlab script that will enable viewing and animating the mode shapes.*

A graphical representation of the modal assurance criterion (MAC) is also presented for each configuration. The MAC provides a measure of the linear independence of one mode from another. Mathematically, it is the scalar product of the each mode shape with the other mode shapes. If two mode shapes are completely linearly independent, the MAC between them will have a value of 0; if the two mode shapes are linearly dependent, the MAC will have a value of 1. In an ideal analysis, the extracted mode shapes are linearly independent. A MAC matrix is a convenient way of displaying the MAC between two sets of mode shapes. If a MAC matrix is computed for a set of modes extracted from an ideal analysis, the diagonal terms of the matrix will have a value of 1.0, and the off diagonal terms will have a value of 0.0.

3.2 Accuracy and Certainty. Unlike previous vehicle tests, the HCH did not have any components added to the basic hull. As a result, both test configurations behaved extremely linearly. The modal parameters and shapes could be extracted with a high degree of confidence. The estimates for the modal frequencies can be considered accurate within 5%, and the damping estimates can be considered accurate within 10% for most of the frequency range in which parameters have been extracted.

3.3 Configuration 1: Four Shakers on Floor. The first configuration discussed consists of the HCH excited by four shakers on the floor, one shaker at each corner of the hull. The four shakers were attached to the hull on primary structural supports. The configuration was intended to excite the global modes of the HCH. Although data was acquired up to 200 Hz, modal parameters were only extracted up to 100 Hz. The modal parameters above 100 Hz were difficult to extract with the

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* Please contact the author via e-mail (mberman@arl.mil) to obtain this addendum.

same certainty as the modes below 100 Hz. A plot of the driving point FRF's is shown in Figure 6. A graphical representation of the MAC matrix appears in Figure 7. The first flexible mode occurs at 36.4 Hz, well above the highest rigid body mode. The separation between the rigid-body modes and the flexible modes is sufficient to assume that there is no interaction between the modes. A list of the extracted modal parameters appears in Table 1.

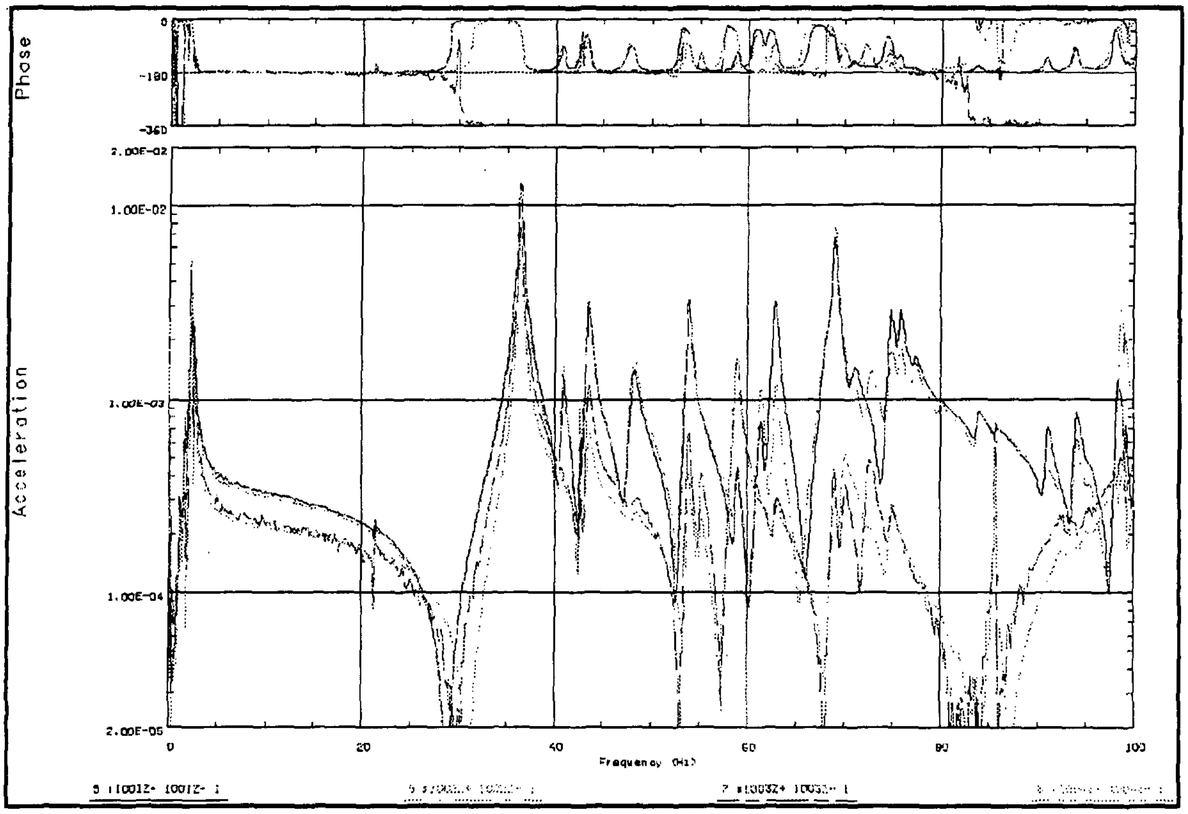

Figure 6. Configuration 1 Driving Point FRFs.

Mode 5, the first flexible mode of the hull (36.4 Hz) is a global torsional mode (Figure 8a). This is the same characteristic mode that also appeared first in the modal analysis of the Bradley Fighting Vehicle (BFV) and the M113 Armored Personnel Carrier (APC). The next global mode of the HCH is mode 7 (Figure 8b). Mode 7 is clearly a global bending mode. The bending mode was not readily apparent in the other vehicles' analysis.

The other modes extracted from the configuration 1 analysis are various types and combinations of local modes. Two typical local modes appear in Figure 9. Mode 6 involves the vibration of the

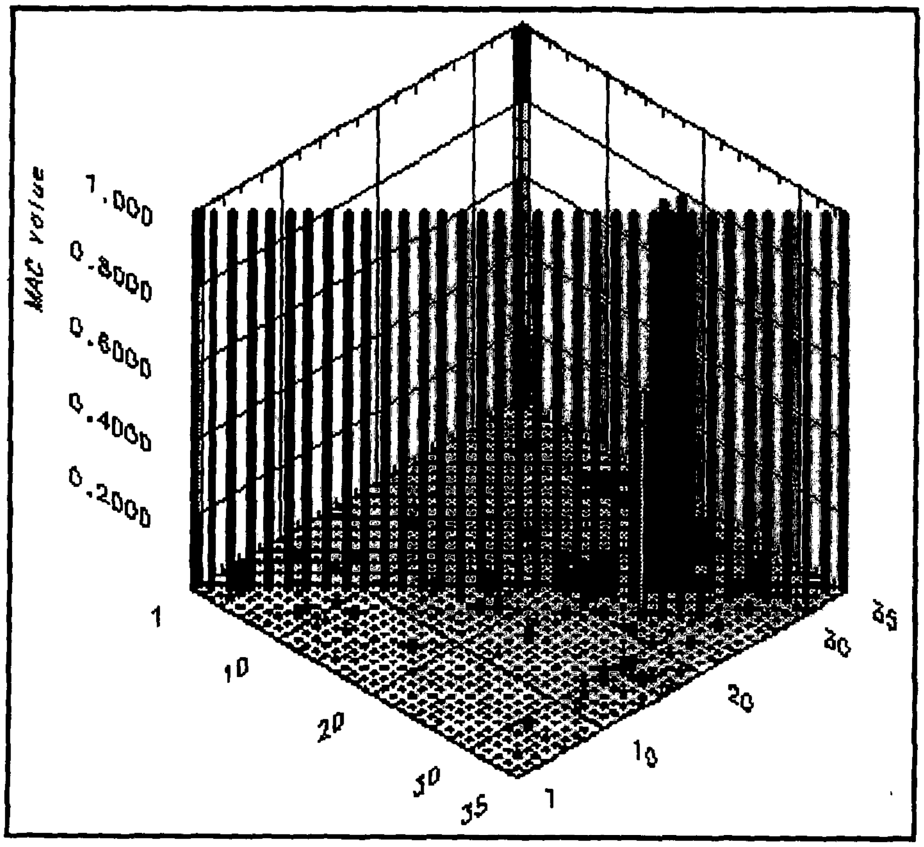

Figure 7. Configuration 1 MAC Matrix.

rear sections of the floor and ceiling. In Mode 8, the edges of the hull deck vibrate vertically resulting in motion of the sponson supports. The remainder of the modes extracted contain various combinations of these basic motions—in some of the remaining modes, only the floor flexes, in other modes, only the roof flexes. The electronic addendum to this paper effectively describes the remaining mode shapes. Appendix B of this paper contains a graphical representation of each extracted mode shape for configuration 1.

3.4 Configuration 2: Two Shakers on Roof, Two Shakers on Floor. The second configuration tested was also excited by four shakers. However, two shakers were attached to the roof and two shakers were attached to the floor. Unlike in configuration 1, the shakers were intentionally not placed on major structural supports. The shakers were placed in an attempt to excite local panel modes of the HCH. As in configuration 1, data was acquired to 200 Hz, but only usable to 100 Hz. Table 2 lists the extracted modal parameters. Figure 10 is a plot of the driving point FRFs. Figure 11 is a graphical representation of the MAC matrix.

Table 1. Configuration 1 Modal Parameters

Mode No.	Frequency (Hz)	Damping (% Critical)	Mode No.	Frequency (Hz)	Damping (% Critical)
1	1.2	1.946	19	74.9	0.418
2	1.7	1.981	20	75.8	0.349
3	2.2	0.671	21	76.5	0.369
4	2.7	2.271	22	77.3	0.337
5	36.4	0.425	23	79.9	0.287
6	40.9	0.441	24	80.0	0.327
7	43.5	0.539	25	81.7	0.414
8	48.2	0.728	26	81.7	0.426
9	53.9	0.369	27	83.8	0.431
10	55.1	0.437	28	83.8	0.430
11	58.9	0.442	29	85.7	0.036
12	61.4	0.435	30	85.8	0.477
13	62.9	0.418	31	90.0	0.288
14	68.3	0.619	32	91.0	0.308
15	69.0	0.289	33	92.7	0.516
16	70.1	0.612	34	94.0	0.321
17	70.9	0.638	35	95.2	0.663
18	72.6	0.767	—	—	—

Almost all of the modes extracted from configuration 2 were also extracted from configuration 1. Mode 3, configuration 2 does not appear to have a counterpart in configuration 1. However, examination of the configuration 2 MAC, reveals a high value between modes 2 and 3. The high MAC value indicates that these two mode shapes are linearly dependent upon one another and are likely to be the same mode. A few additional modes above 95 Hz could be extracted from the configuration 2 measurements.

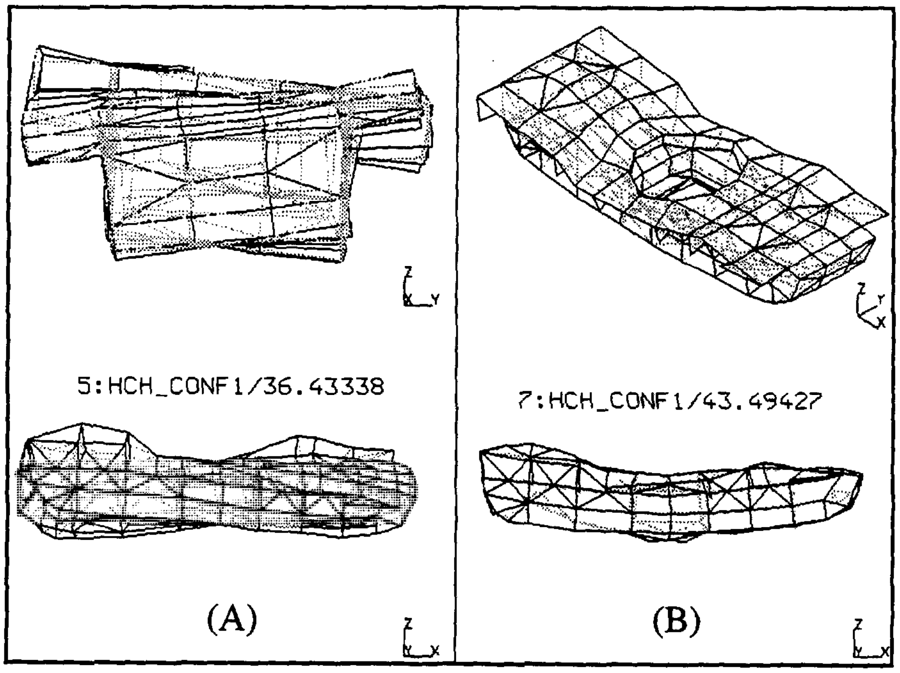

Figure 8. HCH Global Flexible Modes From Configuration 1.

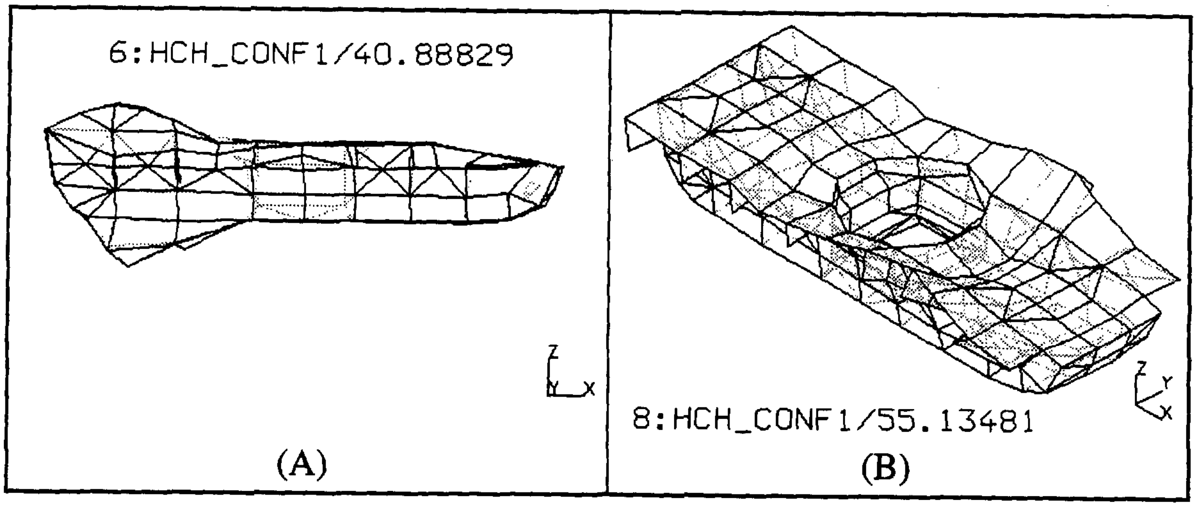

Figure 9. Local Modes of Configuration 1.

Table 2. Configuration 2 Modal Parameters

Mode No.	Frequency (Hz)	Damping (% Critical)	Mode No.	Frequency (Hz)	Damping (% Critical)
1	1.6	0.184	19	75.7	0.337
2	40.9	0.584	20	76.4	0.395
3	40.9	0.446	21	77.2	0.392
4	42.7	0.027	22	79.8	0.299
5	43.5	0.535	23	81.7	0.435
6	48.2	0.768	24	83.7	0.429
7	53.9	0.350	25	85.7	0.030
8	54.0	0.400	26	85.8	0.489
9	55.1	0.437	27	90.1	0.459
10	58.9	0.414	28	90.9	0.317
11	61.4	0.435	29	92.8	0.498
12	62.9	0.418	30	93.8	0.315
13	68.3	0.590	31	95.4	0.532
14	69.0	0.295	32	98.2	0.308
15	70.0	0.590	33	98.6	0.387
16	70.9	0.708	34	98.6	0.226
17	72.6	0.634	35	99.1	0.041
18	74.9	0.411	—	—	—

4. Conclusions

4.1 Comparison Between Shaker Configurations. The mode shapes extracted from configurations 1 and 2 were extremely similar. The primary difference between the two analyses was that configuration 2 was unable to excite the global torsional mode. Figure 12 is the

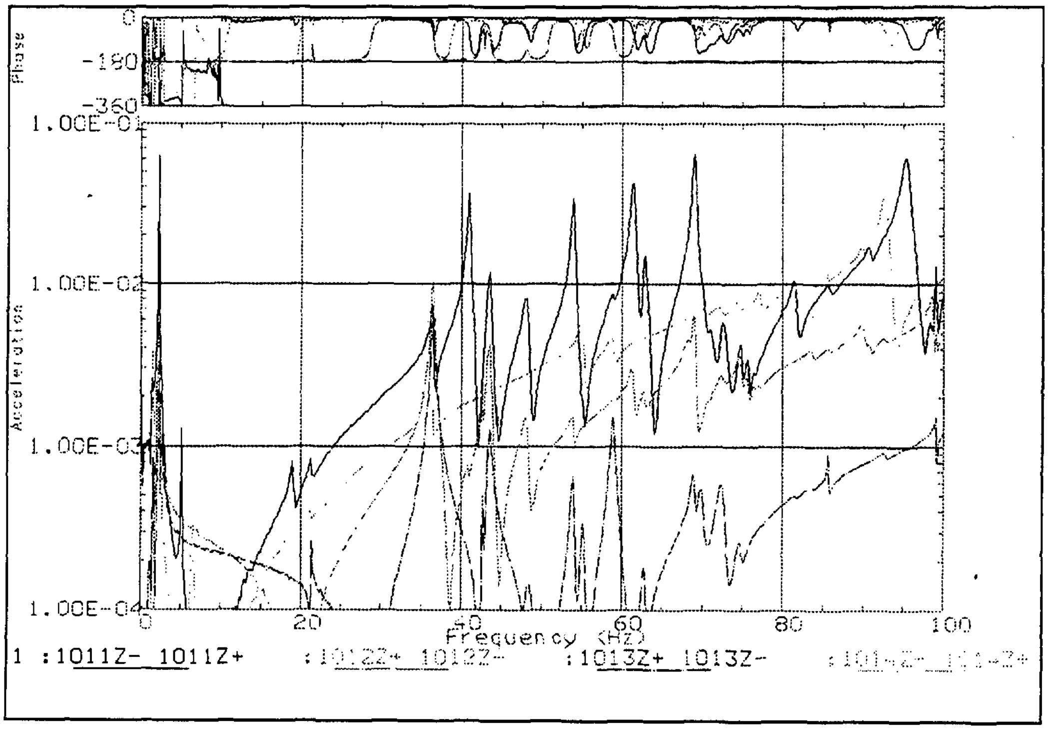

Figure 10. Configuration 2 Driving Point FRFs.

representation of the MAC matrix between configurations 1 and 2. Examination of this plot reveals that configuration 2 provided little additional information to the configuration 1 analysis.

4.2 Summary. The modal parameters that were extracted from the HCH provide an experimental measure of its dynamic properties. This information can be used to refine and validate an FE model. In addition, the damping parameters extracted from this analysis can be incorporated into an FE model, thus enhancing the model's accuracy. The latter is extremely important since an FE technique cannot predict modal damping.

The trends obtained from this modal analysis are similar to the results from previously tested vehicles. The first mode in each of these structure is a global torsional hull mode. This occurs at approximately 40 Hz in each tested vehicle and hull. Although the HCH is significantly larger than

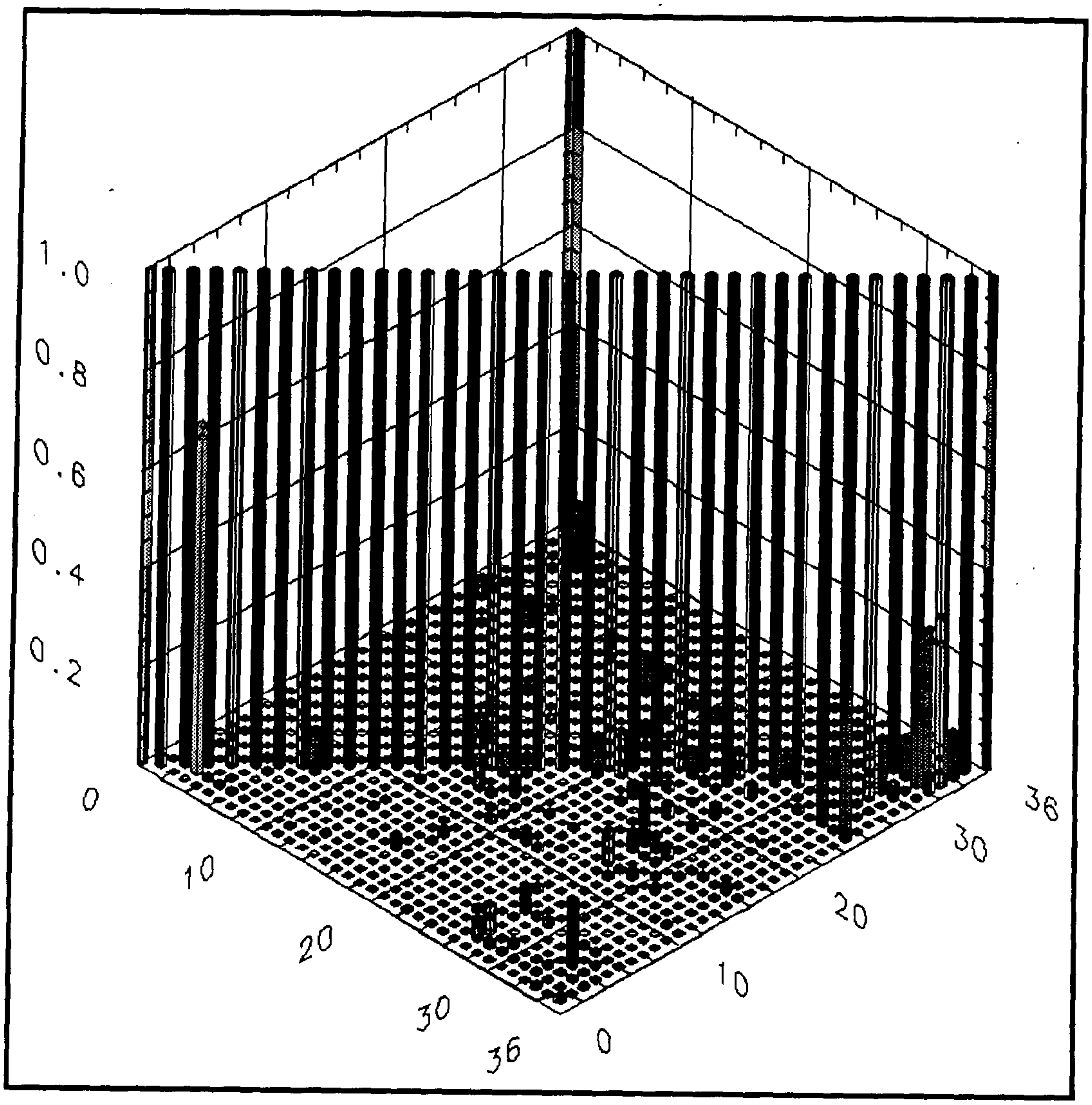

Figure 11. Configuration 2 MAC Matrix.

either vehicle previously tested, it exhibited very similar dynamic properties. The similarity probably exists as a result of similar mass to stiffness ratio for the vehicles.

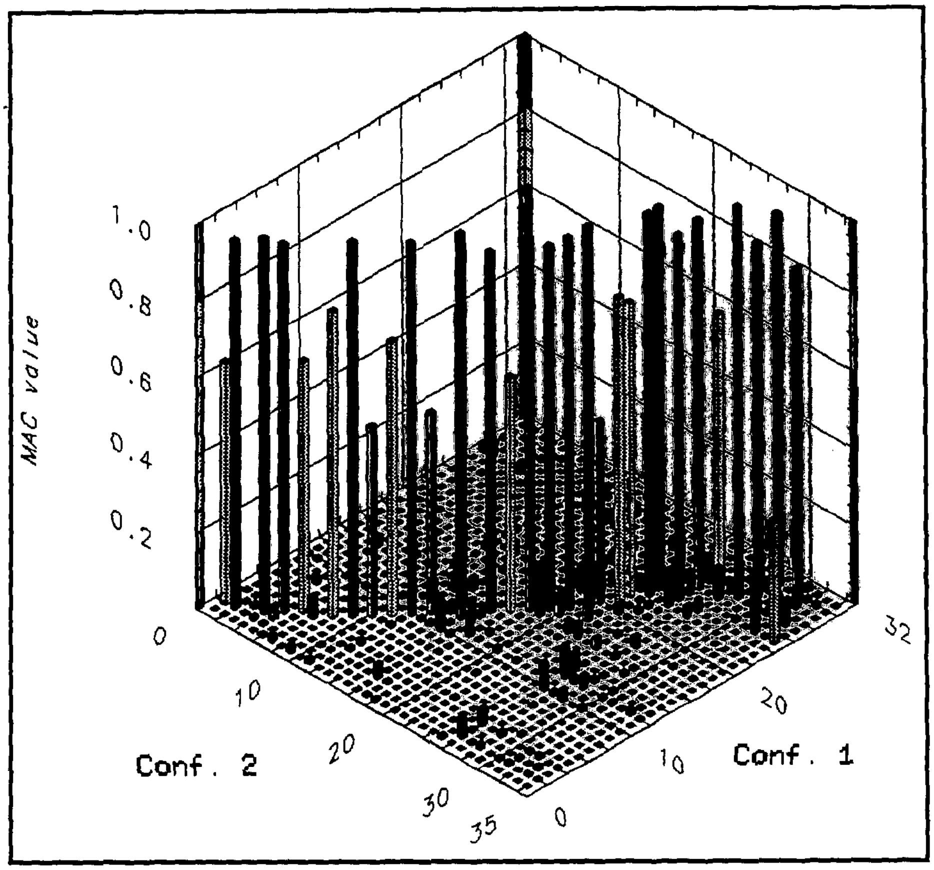

Figure 12. MAC Between Configurations 1 and 2.

7. References

1. University of Cincinnati, Structural Dynamics Research Laboratory. "Advanced Shock Impact Mechanics for Heavy Armored Fighting Vehicles: Experimental Modal Analysis of the HCH Composite Hull." U.S. Army Contract DAAL-1094-R-9249, September–October 1994.

2. Berman, M. S., and T. H. Li. "Modal Analysis of the Bradley Fighting Vehicle (BFV): Prototype Composite Hull and Production Metallic Hull." ARL-TR-445, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1994.

3. Berman, M. S. "Modal Analysis of the M113 Armored personnel Carrier Metallic Hull and Composite Hull." ARL-MR-246, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1995.

4. Braun, S. *Mechanical Signature Analysis: Theory and Applications.* London: Harcourt Brace Jovanovich, 1986.

5. Brown, D. L., R. J. Allemang, and R. Zimmerman. "Parameter Estimation Techniques for Modal Analysis." Technical Paper Series 90221, Society of Automotive Engineers, Inc., 26 February–2 March 1979.

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Appendix A:

Firestone Model 113 Specifications

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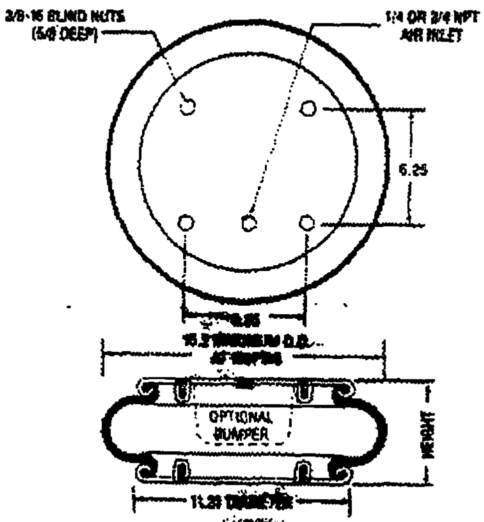
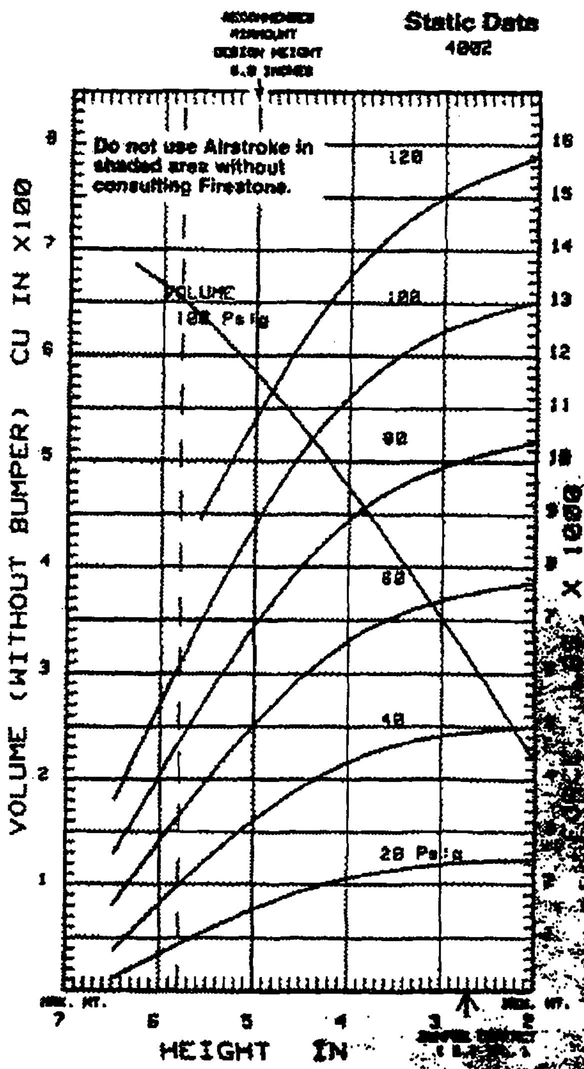
113 **Firestone** Airstroke® actuators · Airmount® isolators

	Description	Order No.
Style 113 Two Ply Bellows	Blind nuts, 1/4 NPT	WO1-358-7103
	Blind nuts, 1/4 NPT, bumper	WO1-358-7104
	Blind nuts, 3/4 NPT	WO1-358-7101
	Blind nuts, 3/4 NPT, bumper	WO1-358-7109
	Steel button head bead rings, 1¾ bolts, nuts, washers	WO1-358-7110
	Blind nuts, 1/8 NPT	WO1-753-7113
	Blind nuts, 1¼ NPT	WO1-753-7114
	Rubber Bellows Only	WO1-358-0135
Assembly weight		14.5 lbs.
Force to collapse to minimum height (@ 0 PSIG)		17 lbs.
Style 128 Four Ply Bellows	Blind nuts, 1/4 NPT	WO1-358-8151
	Blind nuts, 1/4 NPT, rubber bumper	WO1-358-8149
	Blind nuts, 3/4 NPT	WO1-358-8152
	Blind nuts, 3/4 NPT, rubber bumper	WO1-358-8150
	Rubber Bellows Only	WO1-358-0231



NOTE: This part is also available with bead rings (rather than end plates) SEE PAGE 8.

Dynamic Characteristics at 5.0 in. Design Height (Required for Airmount isolator design only)				
Volume @ 100 PSIG = 585 in³			Natural Frequency	
Gage Pressure (PSIG)	Load (lbs.)	Spring Rate (lbs./in.)	CPM	HZ
40	3,220	[illegible]	163	2.72
60	5,030	3,432	155	2.58
80	[illegible]	4,407	150	2.50
100	8,800	5,385	147	2.45



SEE PAGE 12 for instructions on how to use charts.

Force Table (Use for Airstroke actuator design)						
Assembly Height (in.)	Volume @ 100 PSIG (in³)	Pounds Force @ 20 PSIG	@ 40 PSIG	@ 60 PSIG	@ 80 PSIG	@ 100 PSIG
5.0	585	1,540	3,220	5,030	6,890	8,800
4.0	477	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3.0	353	2,390	4,830	7,380	9,800	12,470

Figure A-1. Firestone Air Ride Model 113 Specifications.

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Appendix B:

Heavy Composite Hull (HCH) Configuration 1 Mode Shapes

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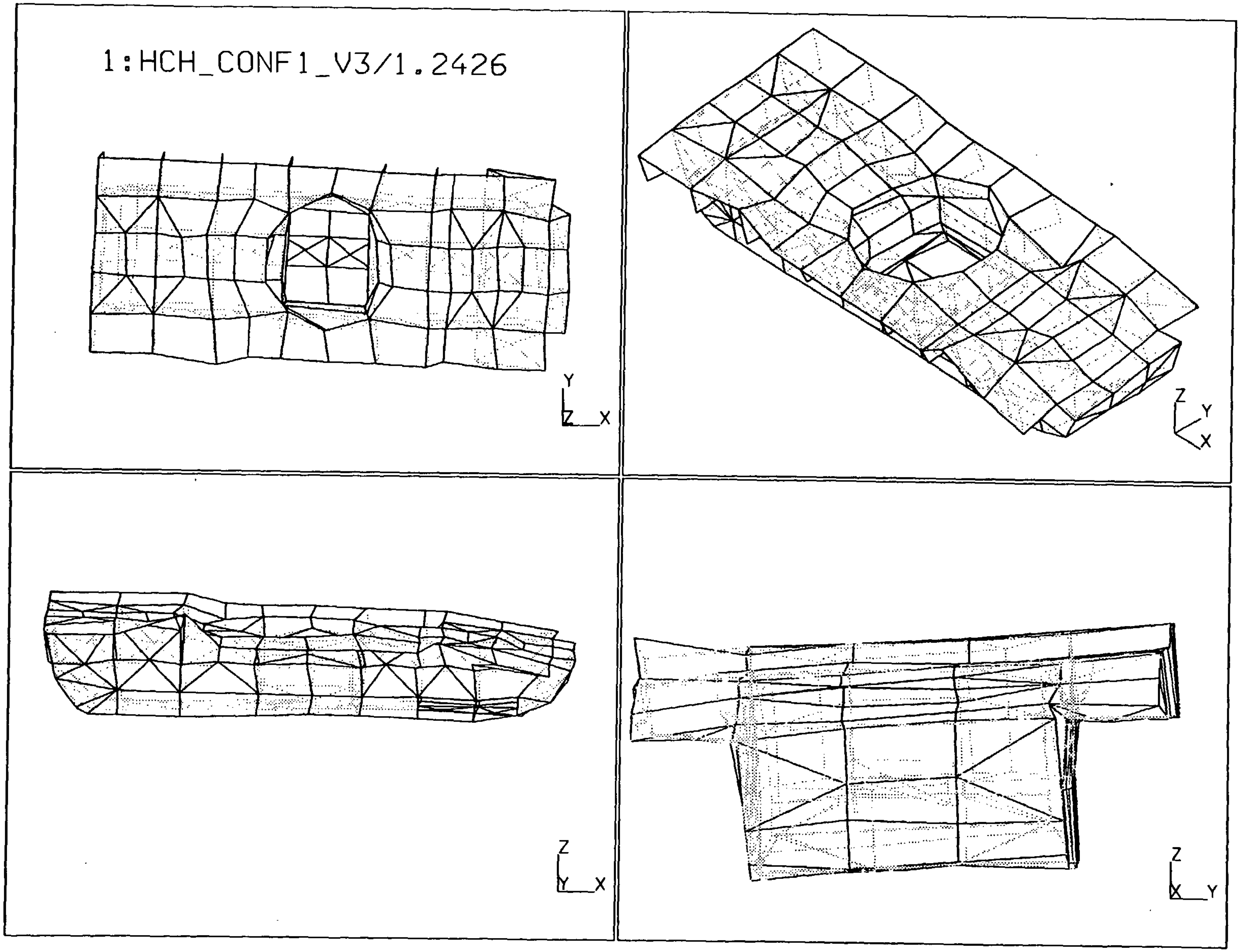


Figure B-1. V3/1.2426.

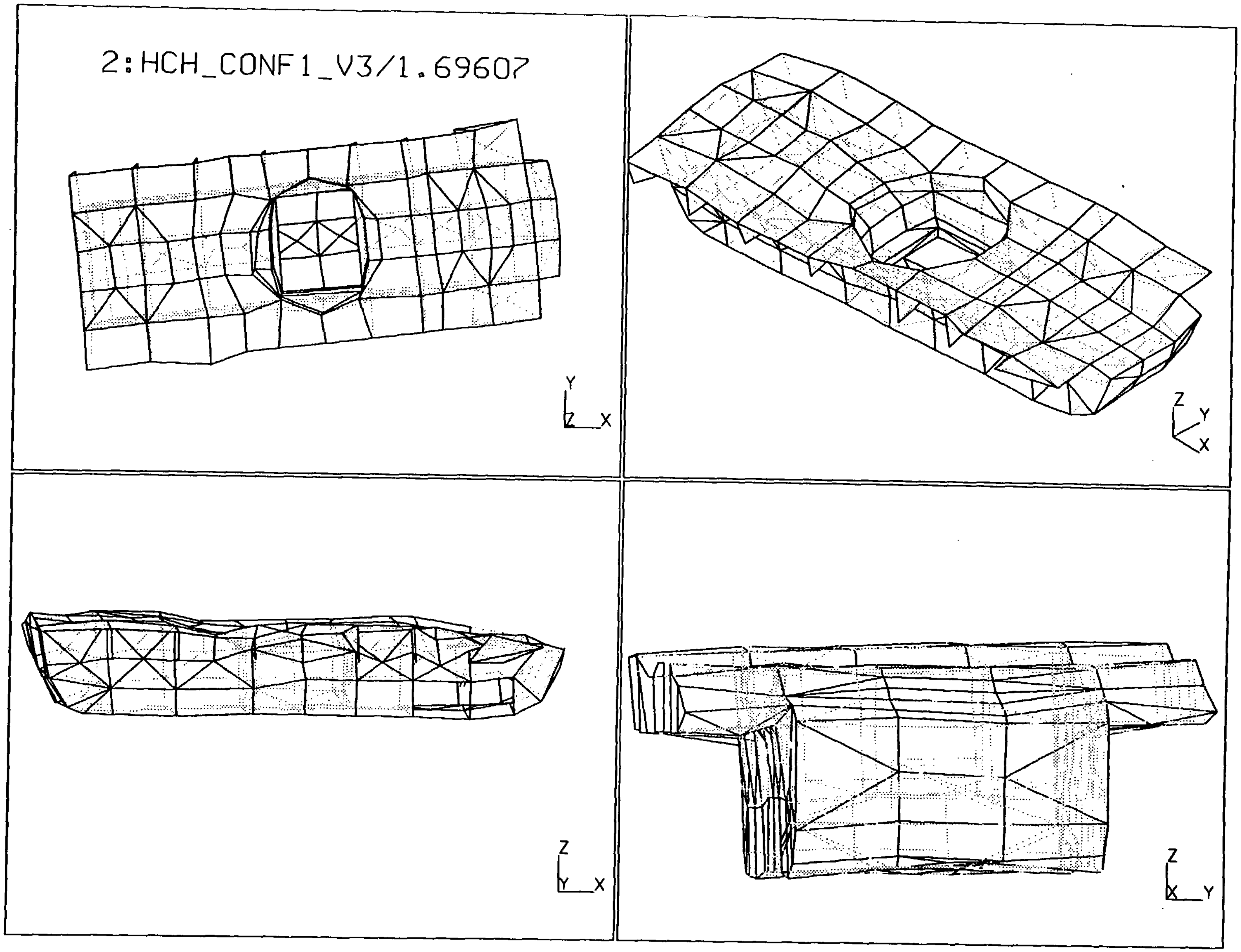


Figure B-2. V3/1.69607.

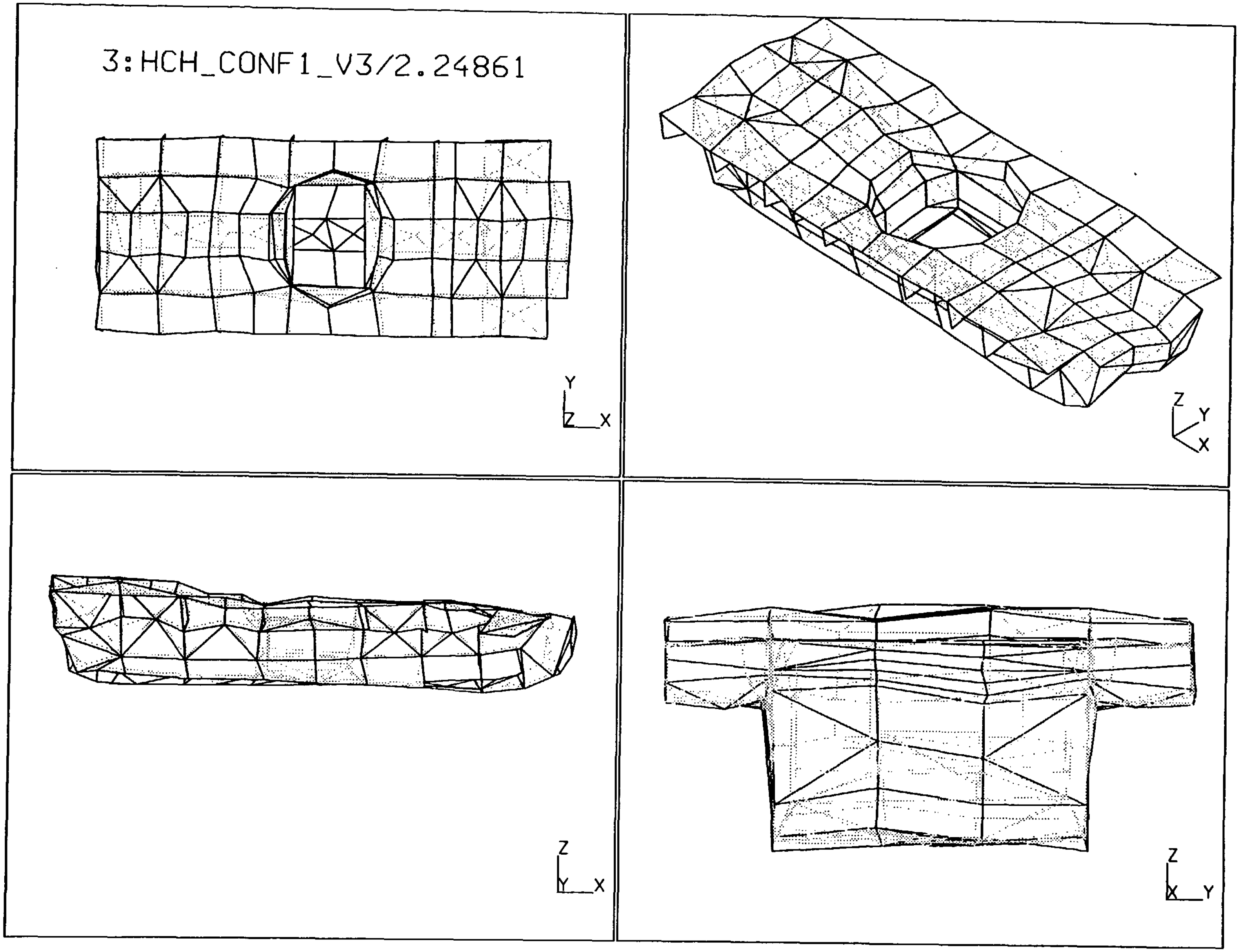


Figure B-3. V3/2.24861.

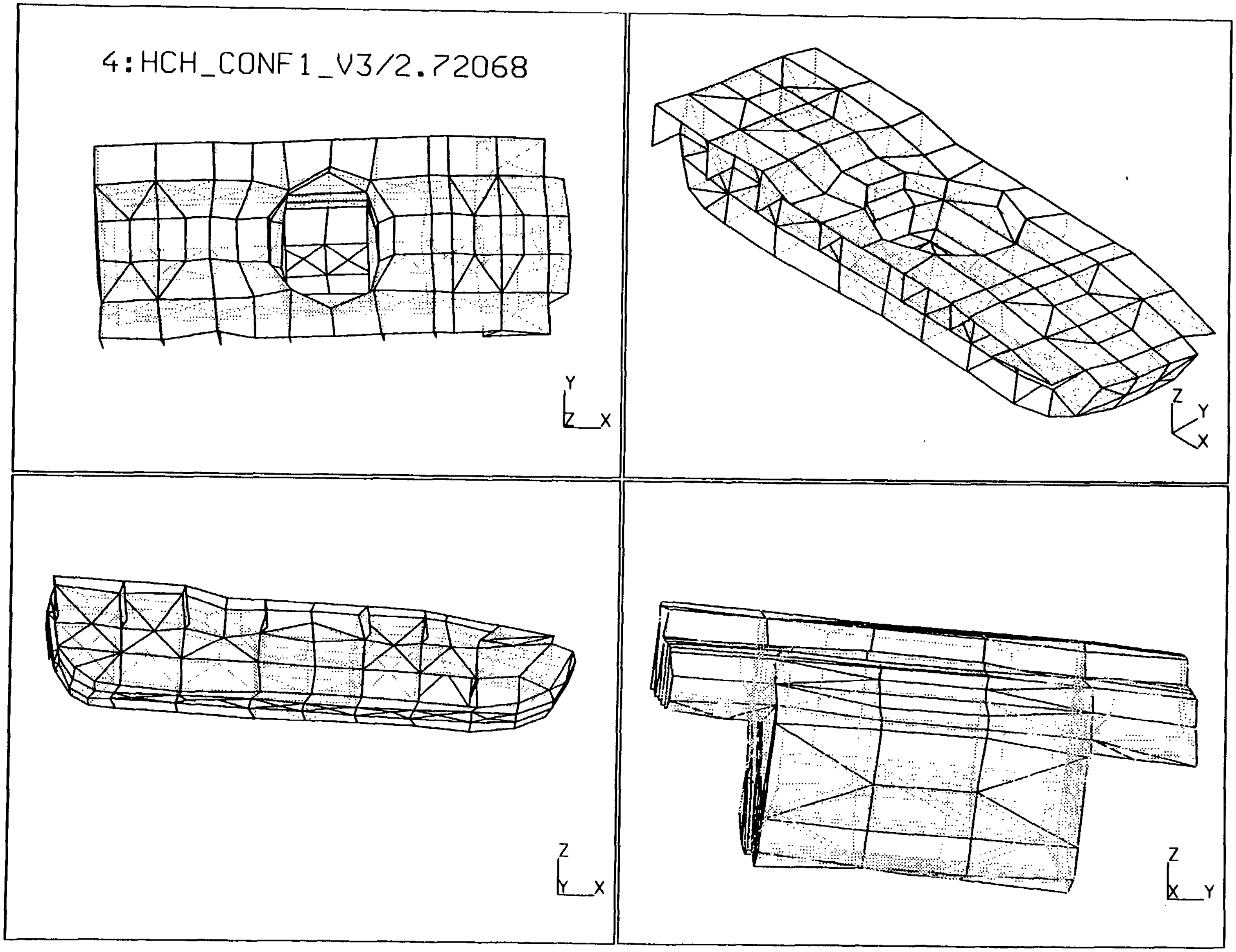


Figure B-4. V3/2.72068.

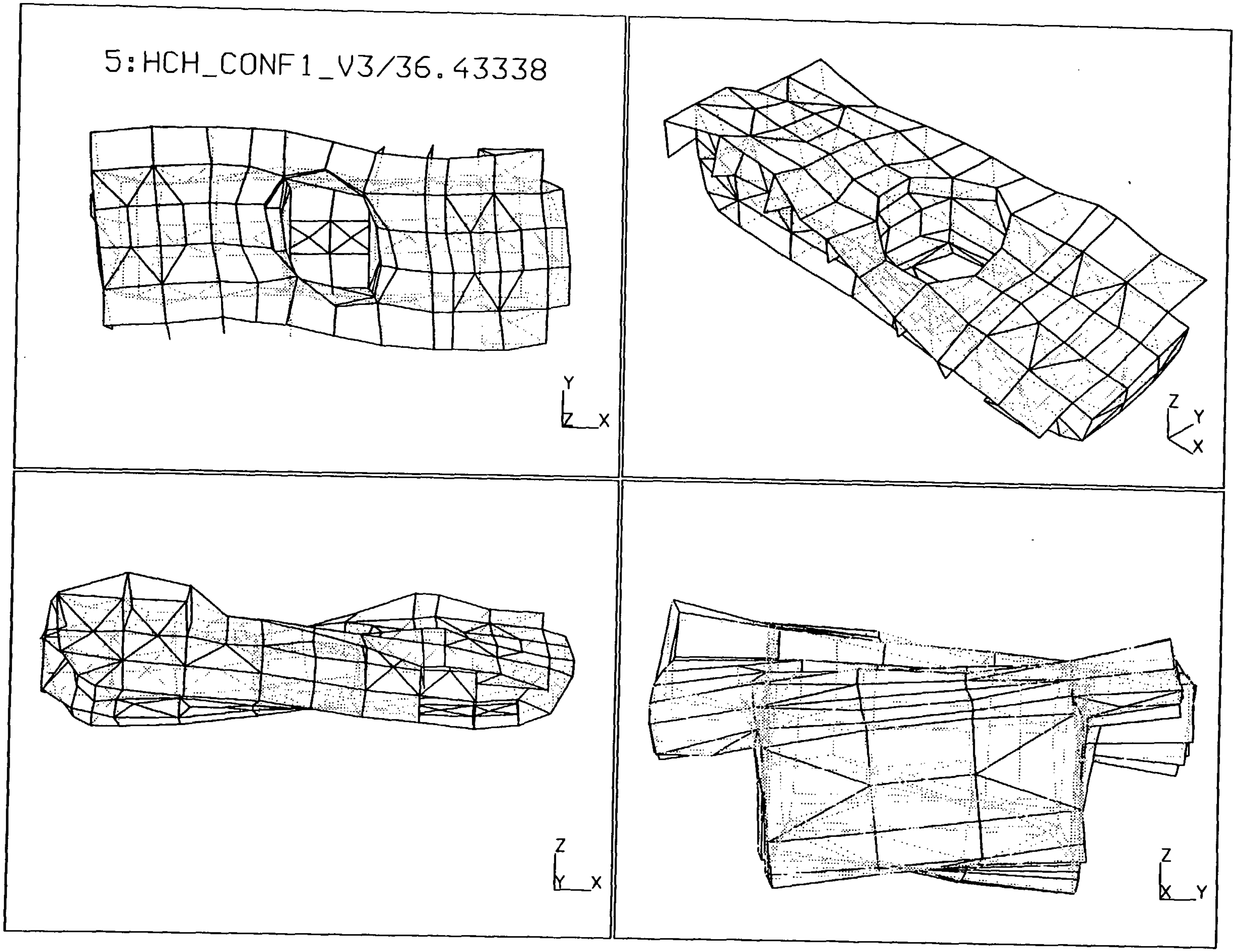


Figure B-5. V3/36.43338.

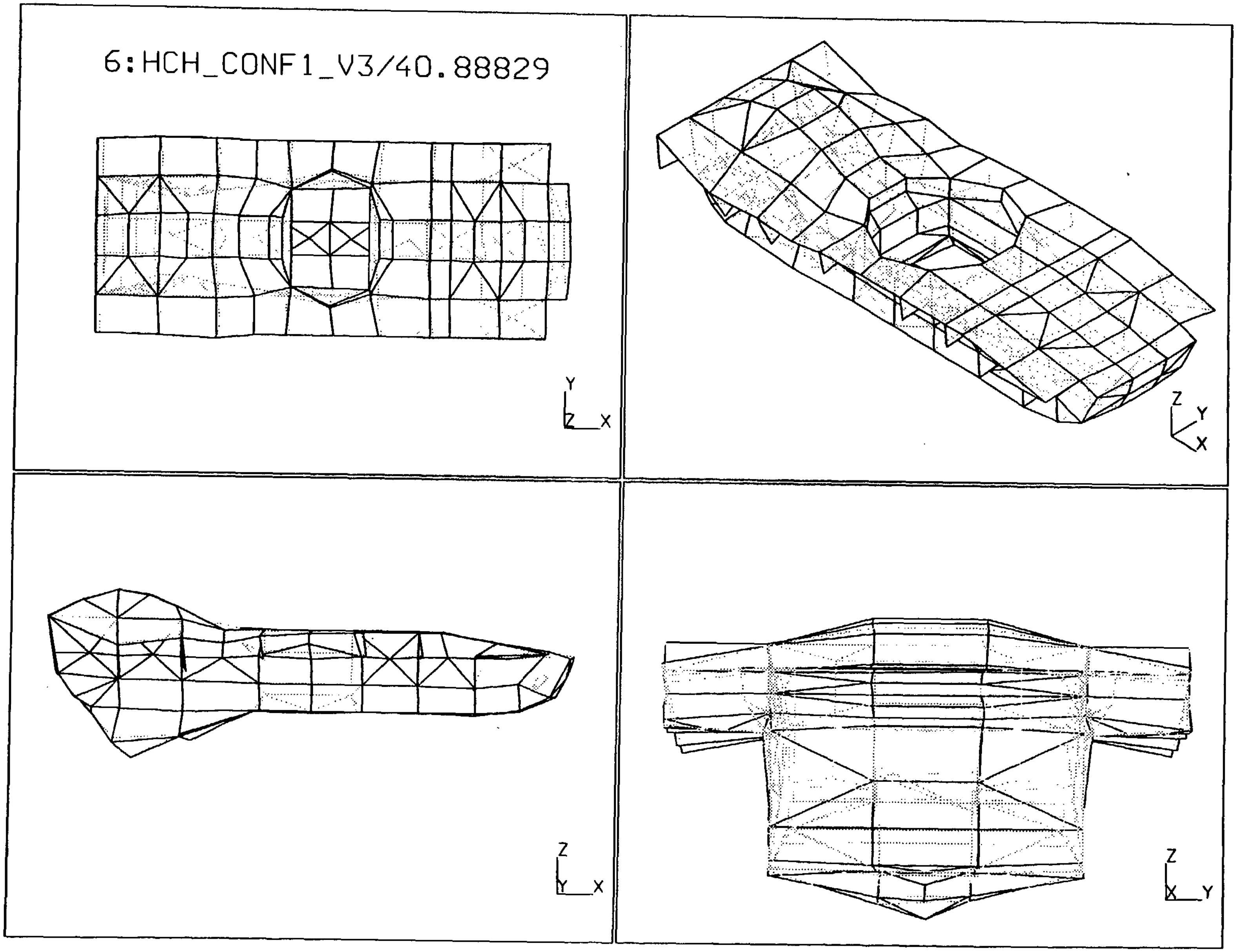


Figure B-6. V3/40.88829.

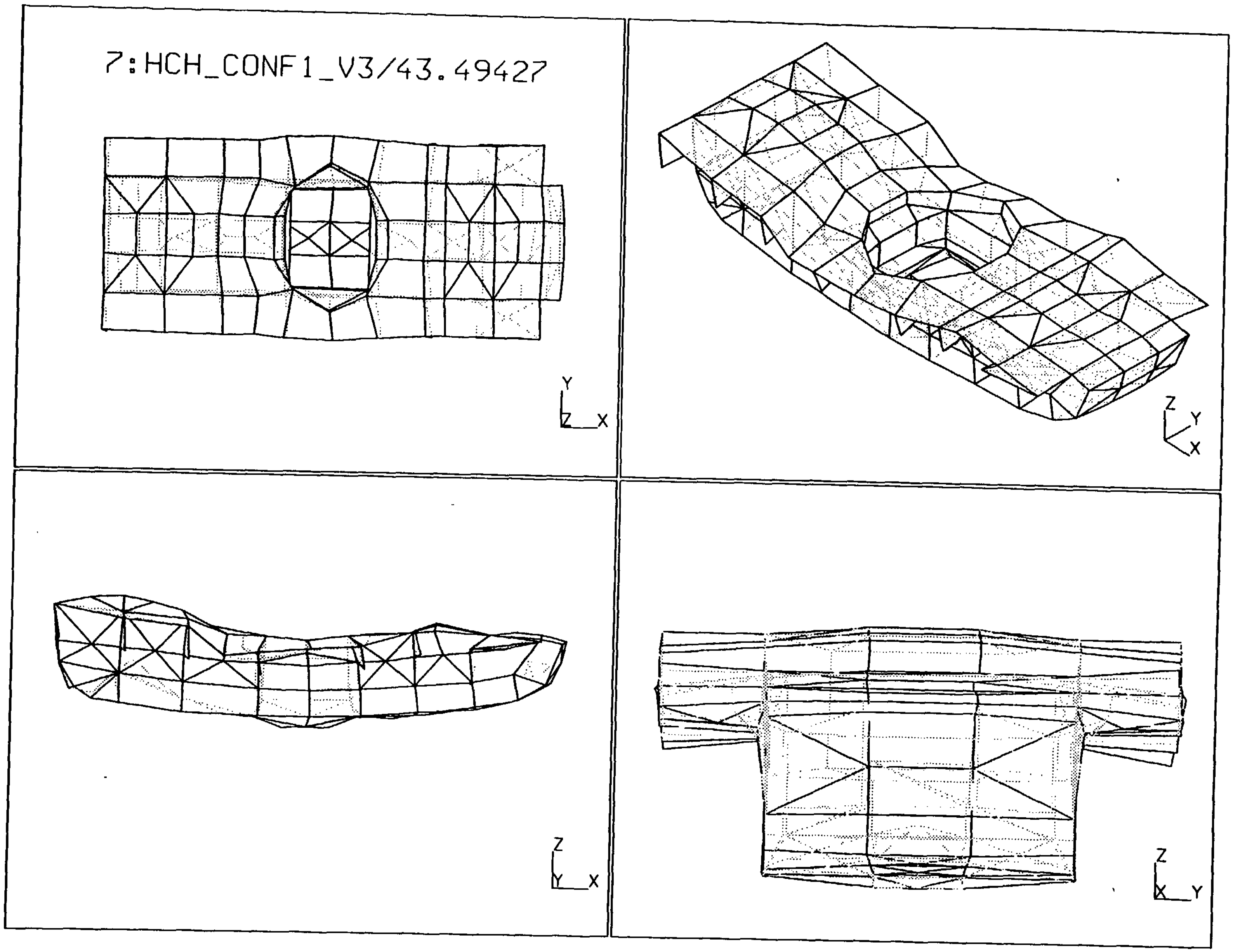


Figure B-7. V3/43.49427.

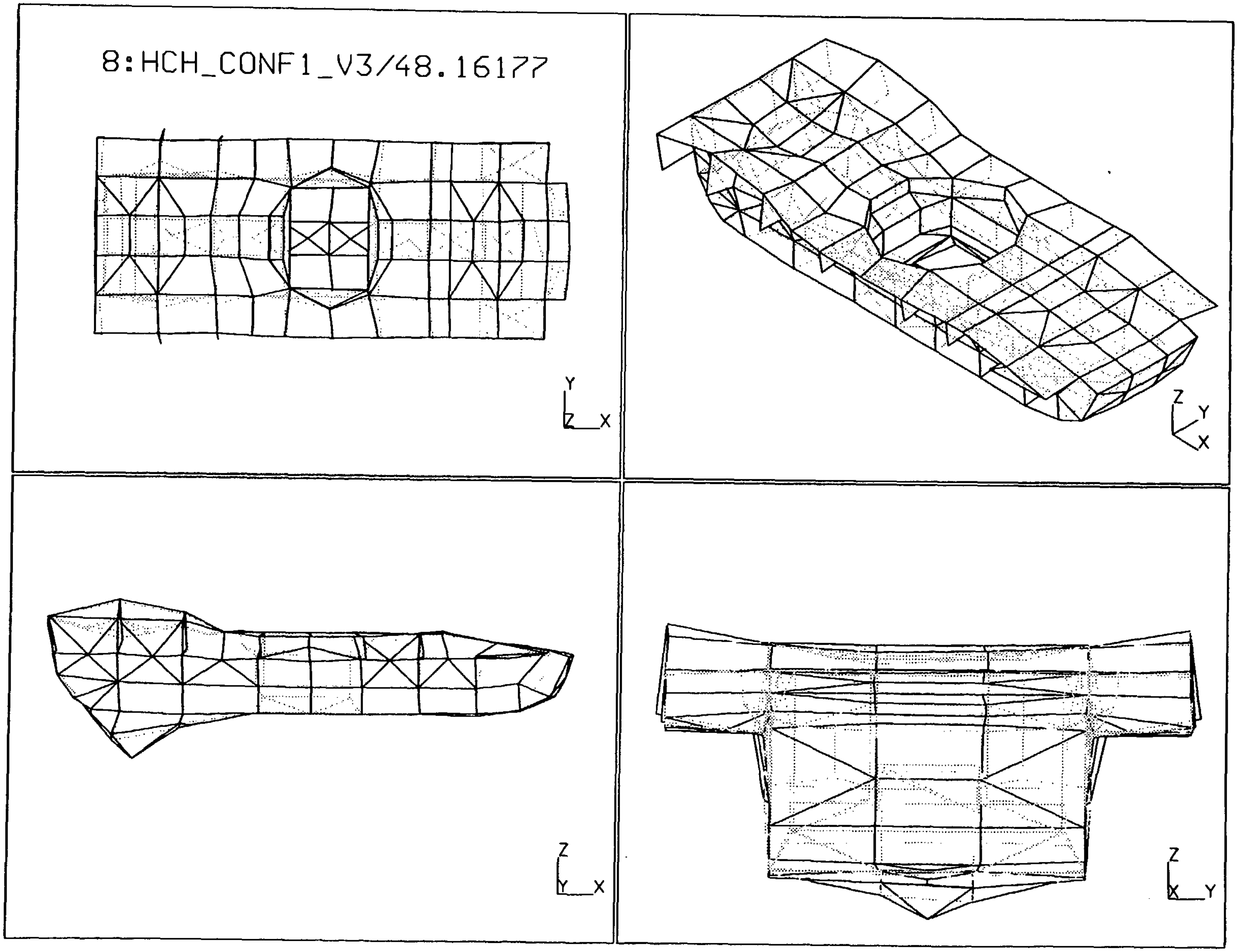


Figure B-8. V3/48.16177.

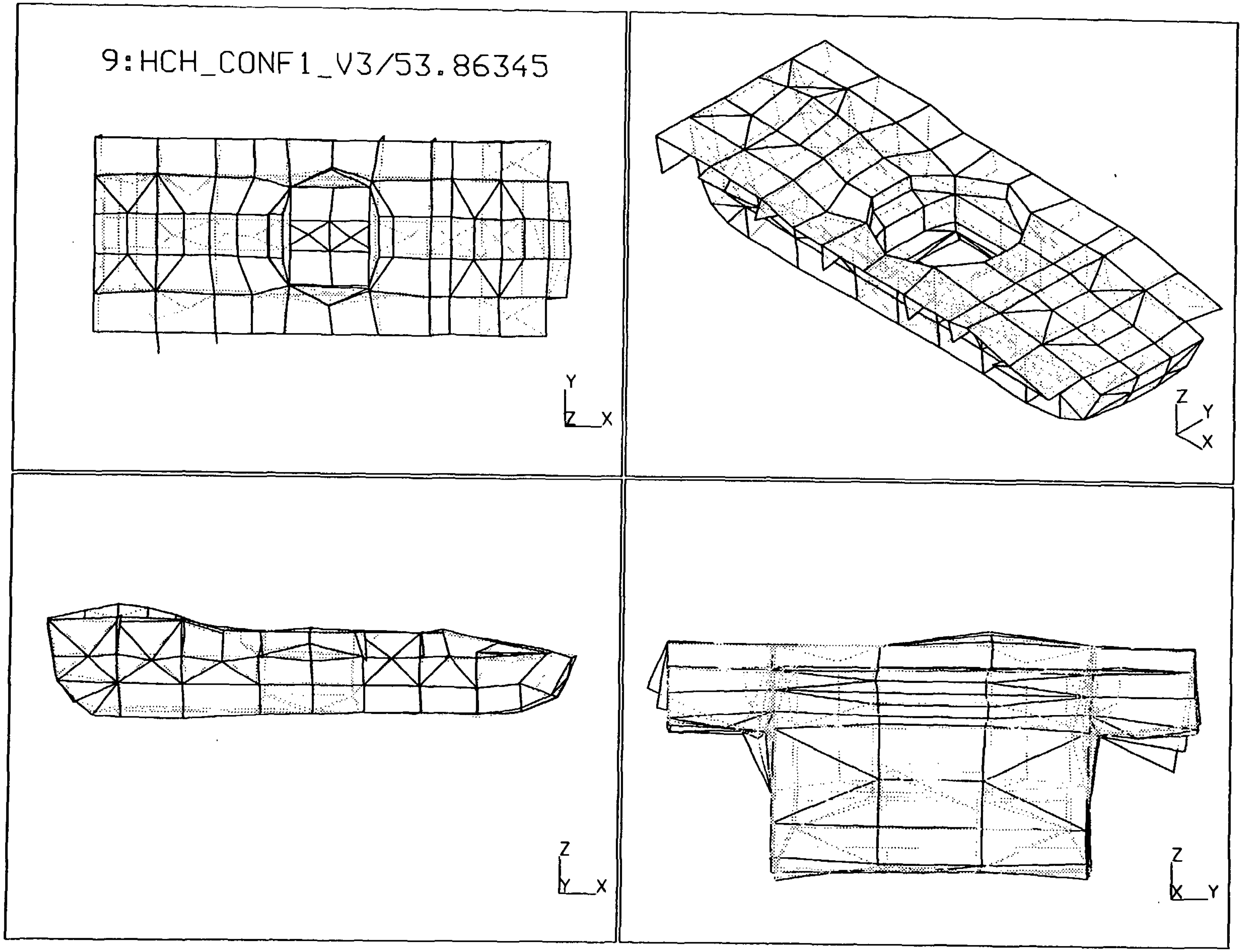


Figure B-9. V3/53.86345.

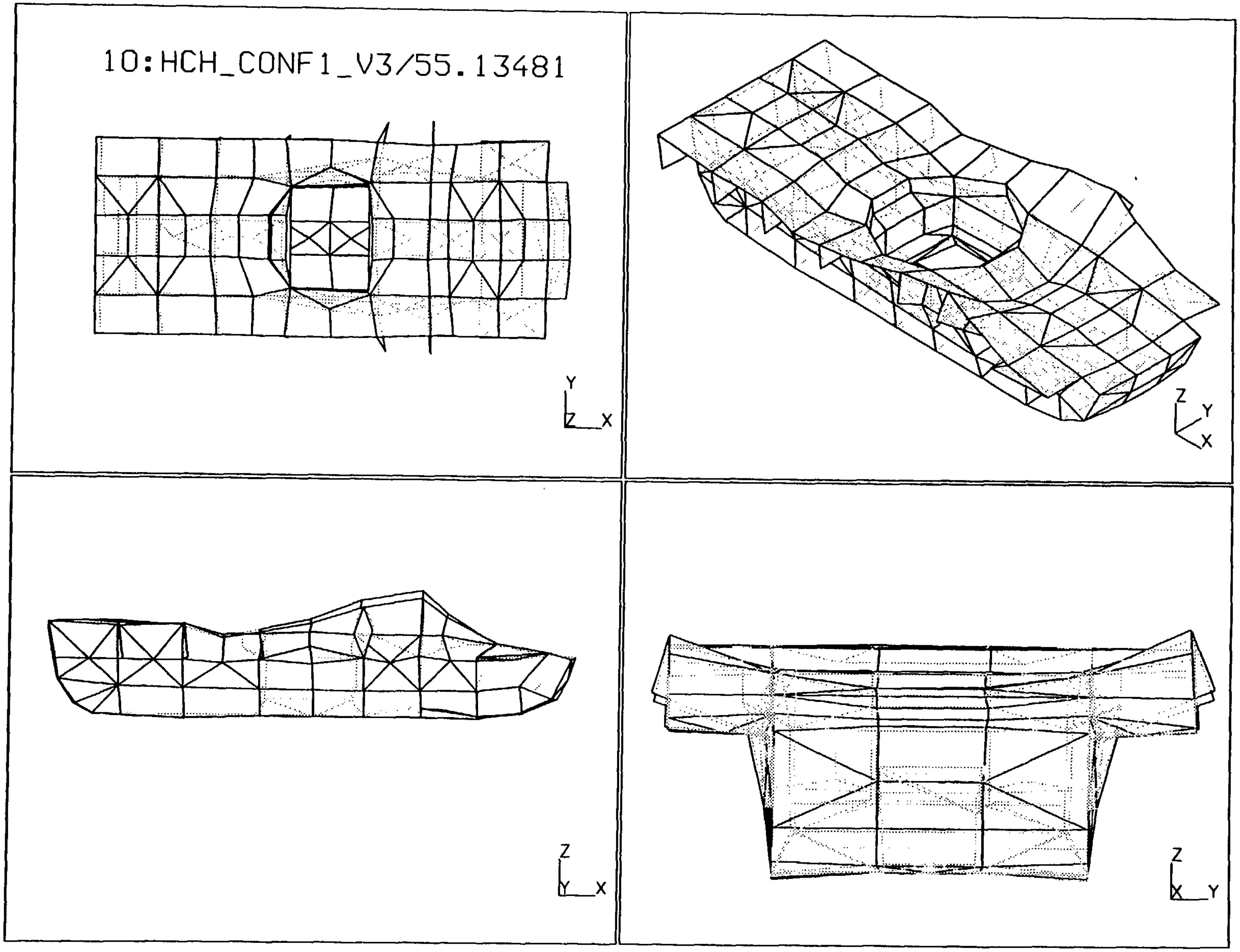


Figure B-10. V3/55.13481.

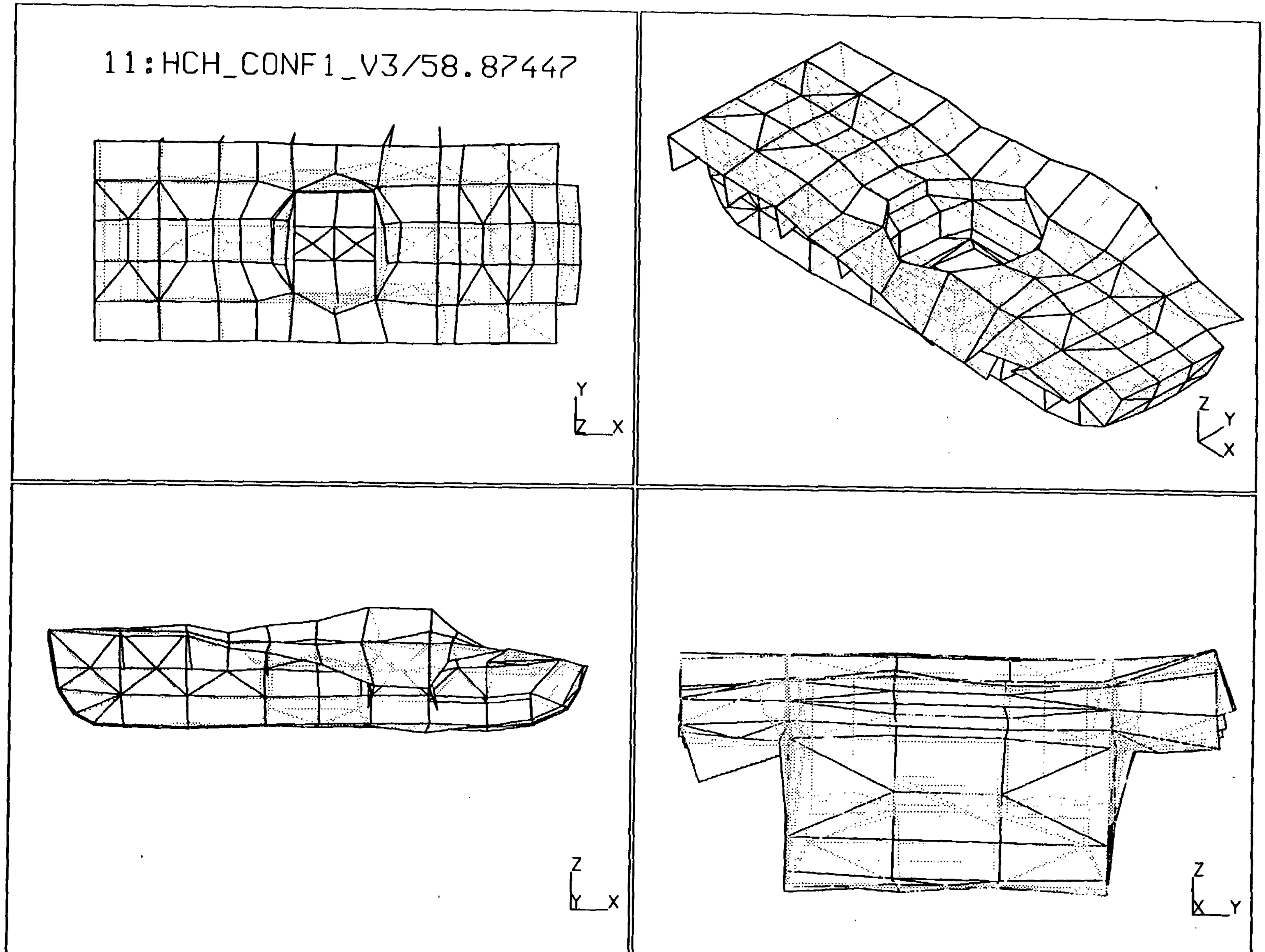


Figure B-11. V3/58.87447.

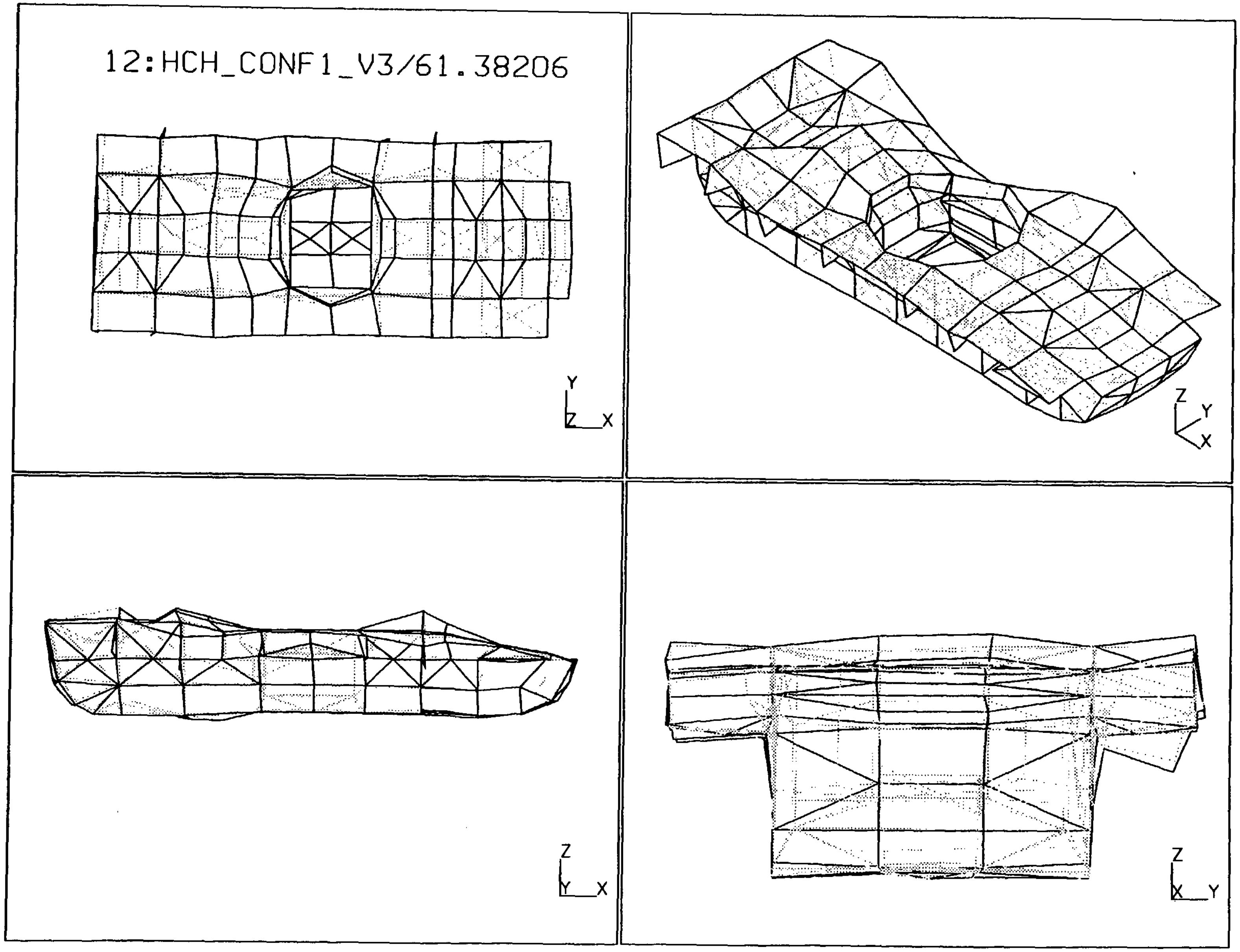


Figure B-12. V3/61.38206.

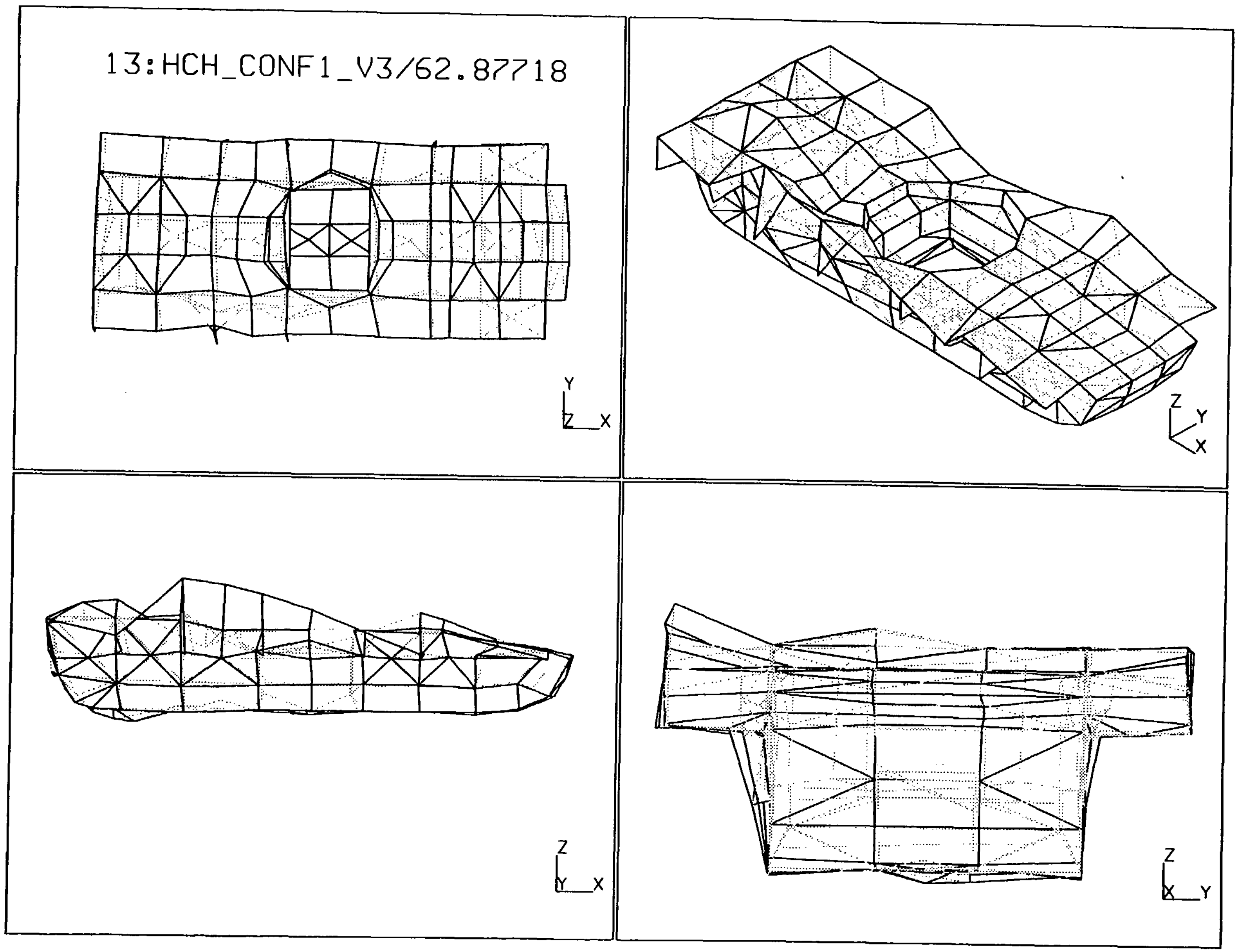
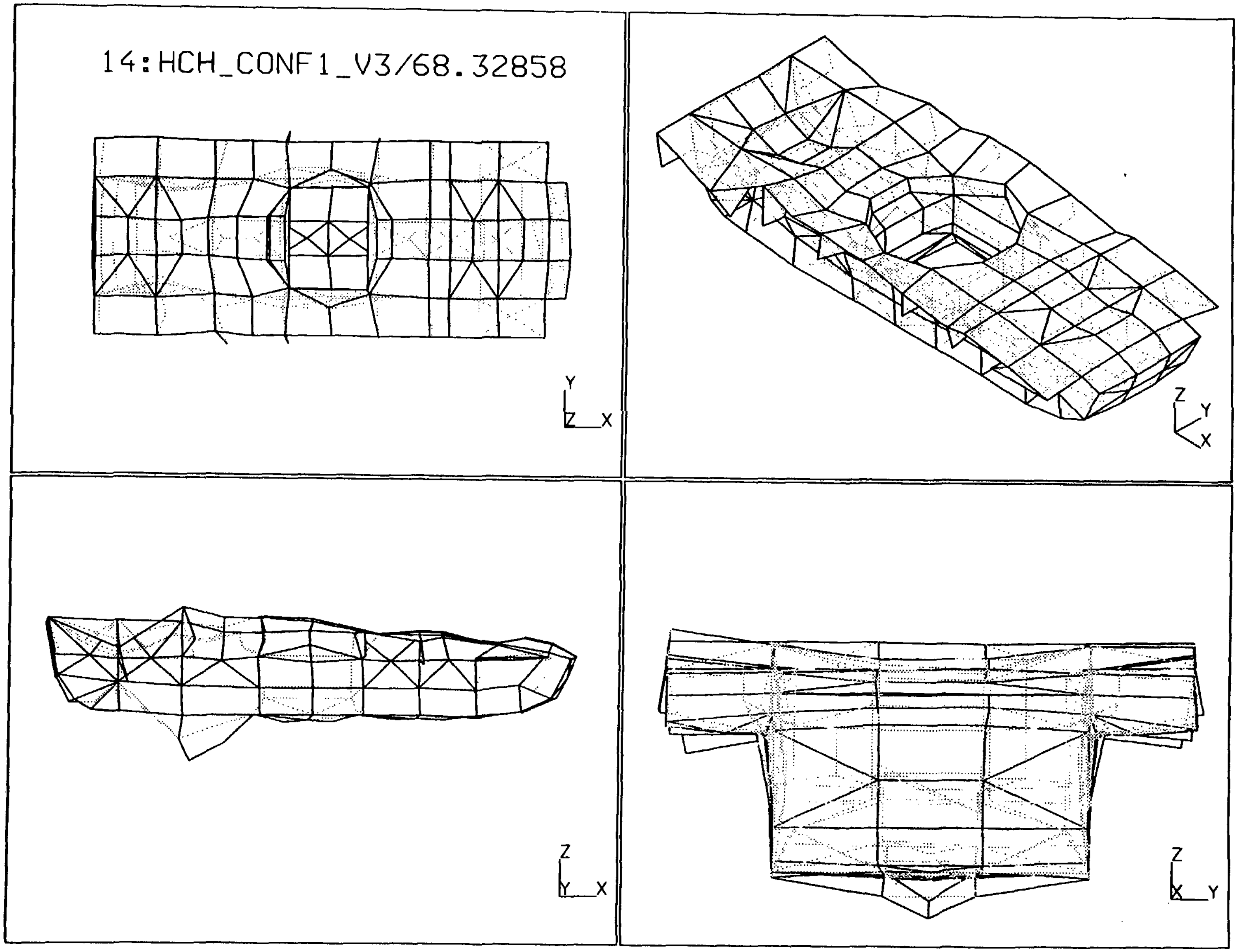


Figure B-13. V3/62.87718.



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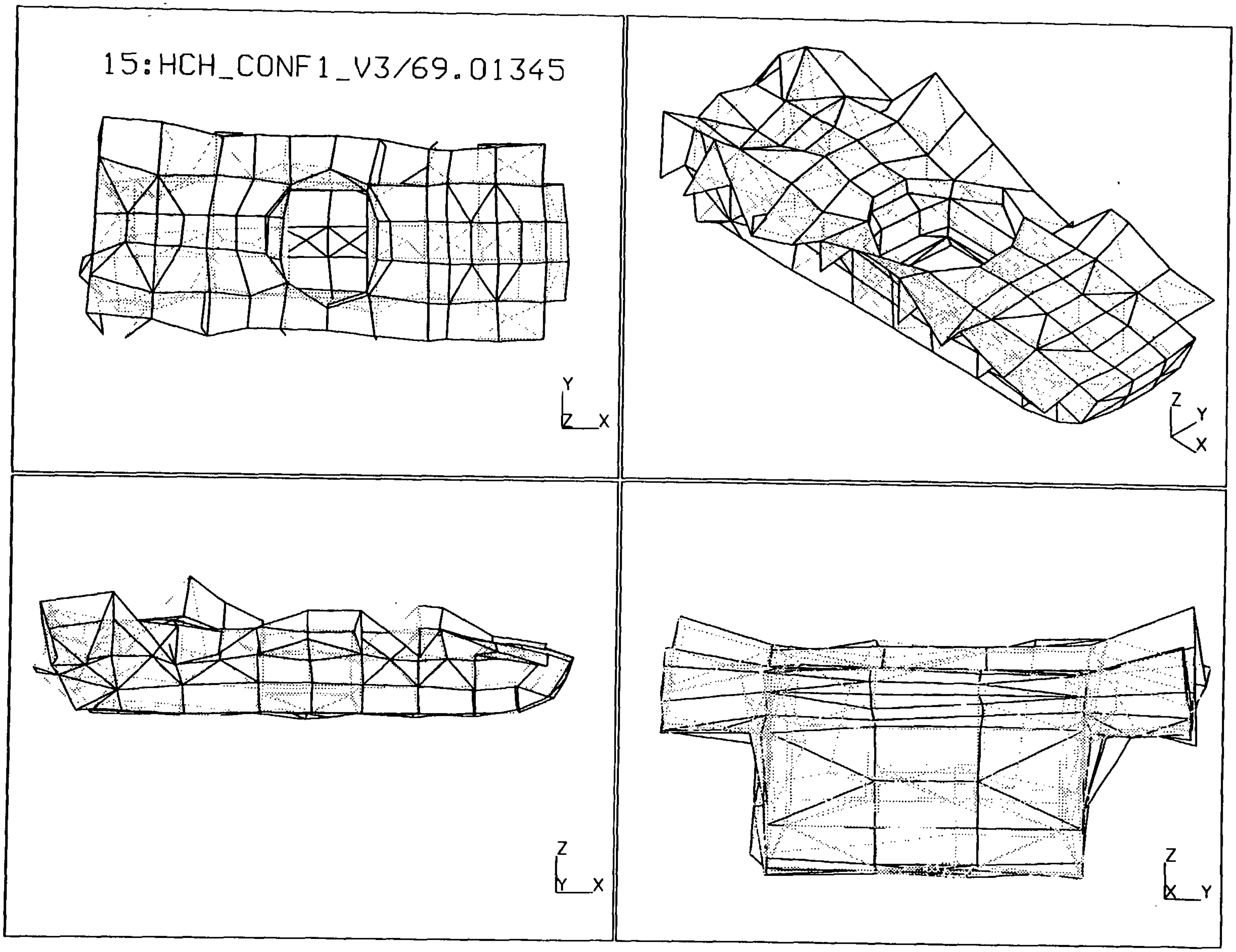

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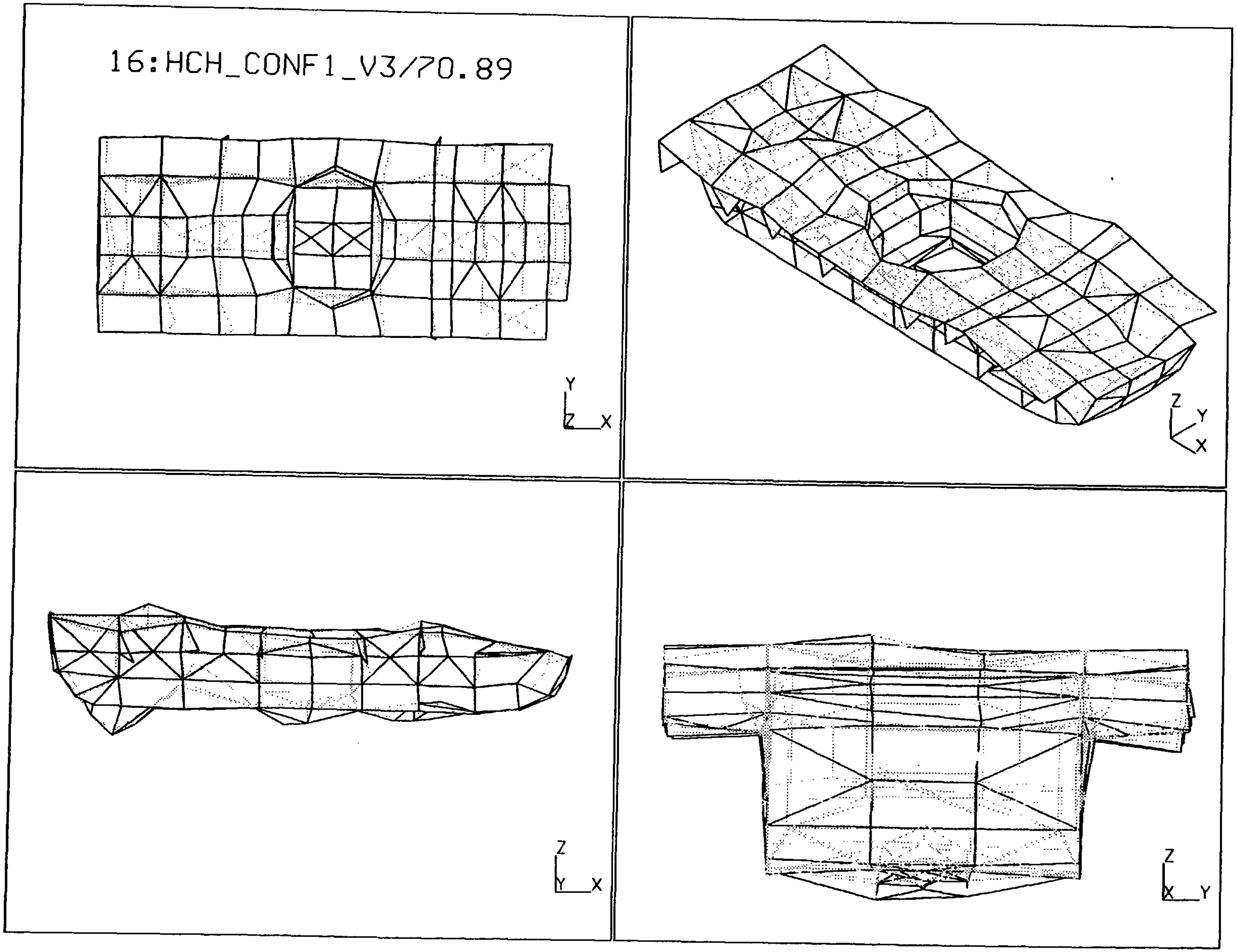

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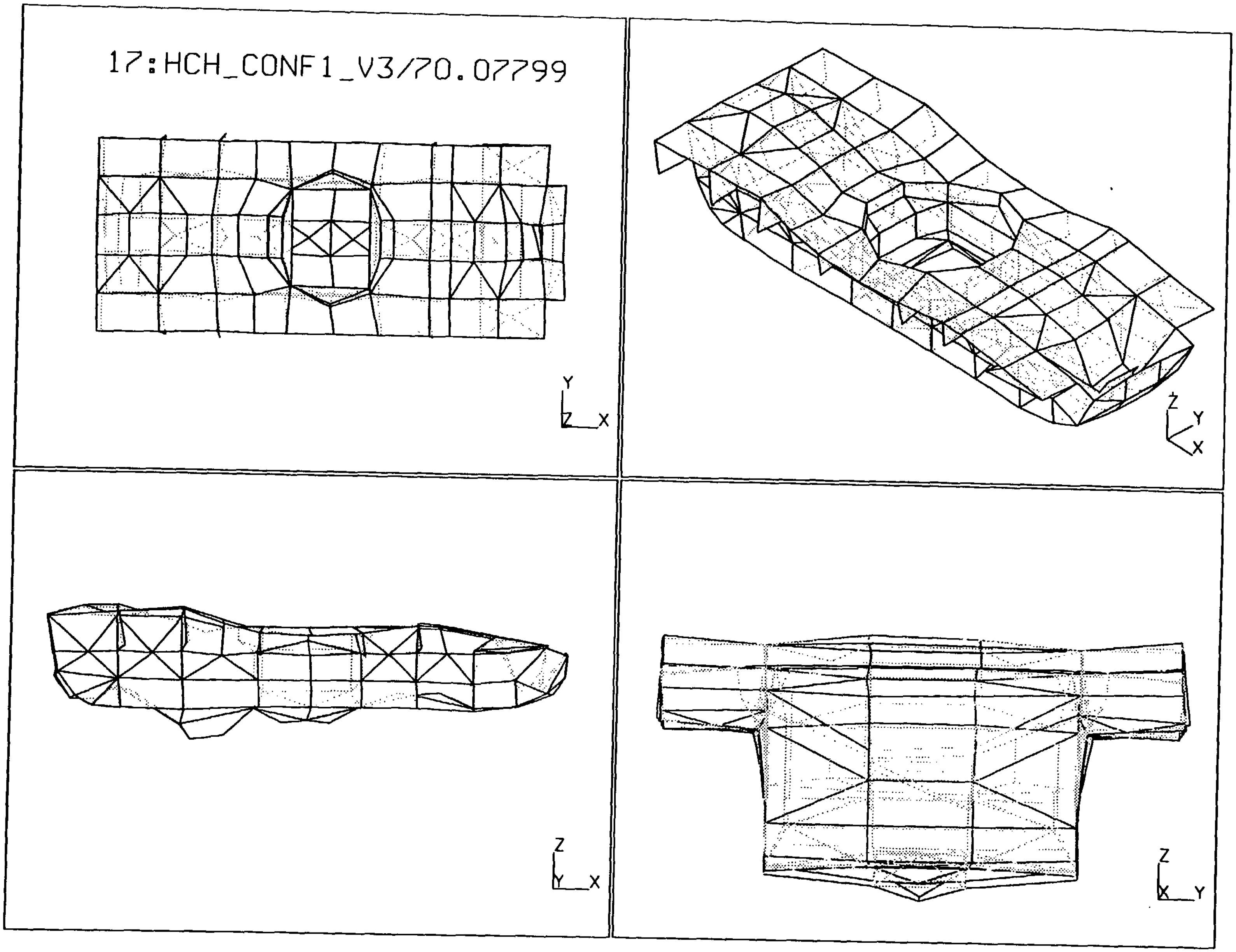

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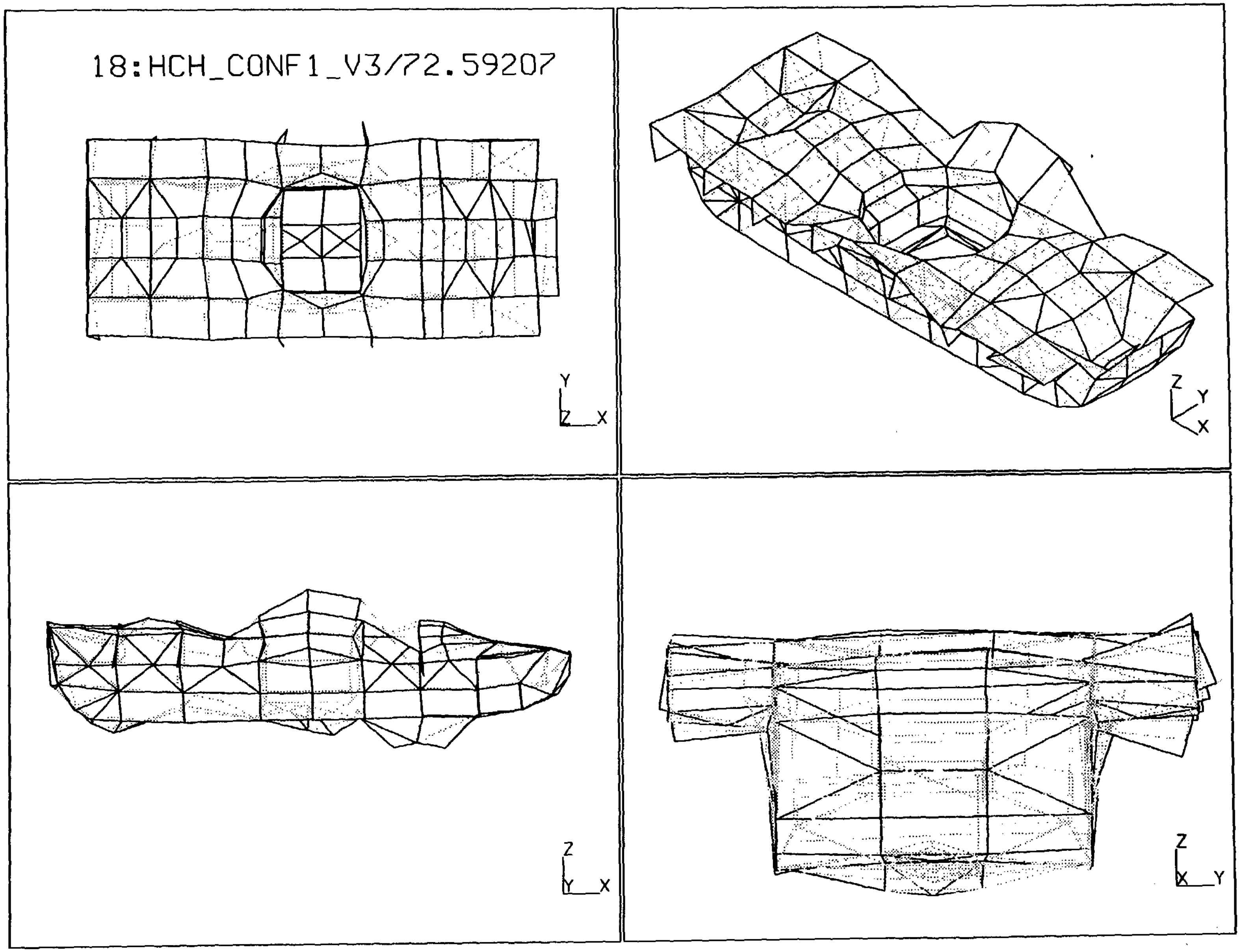

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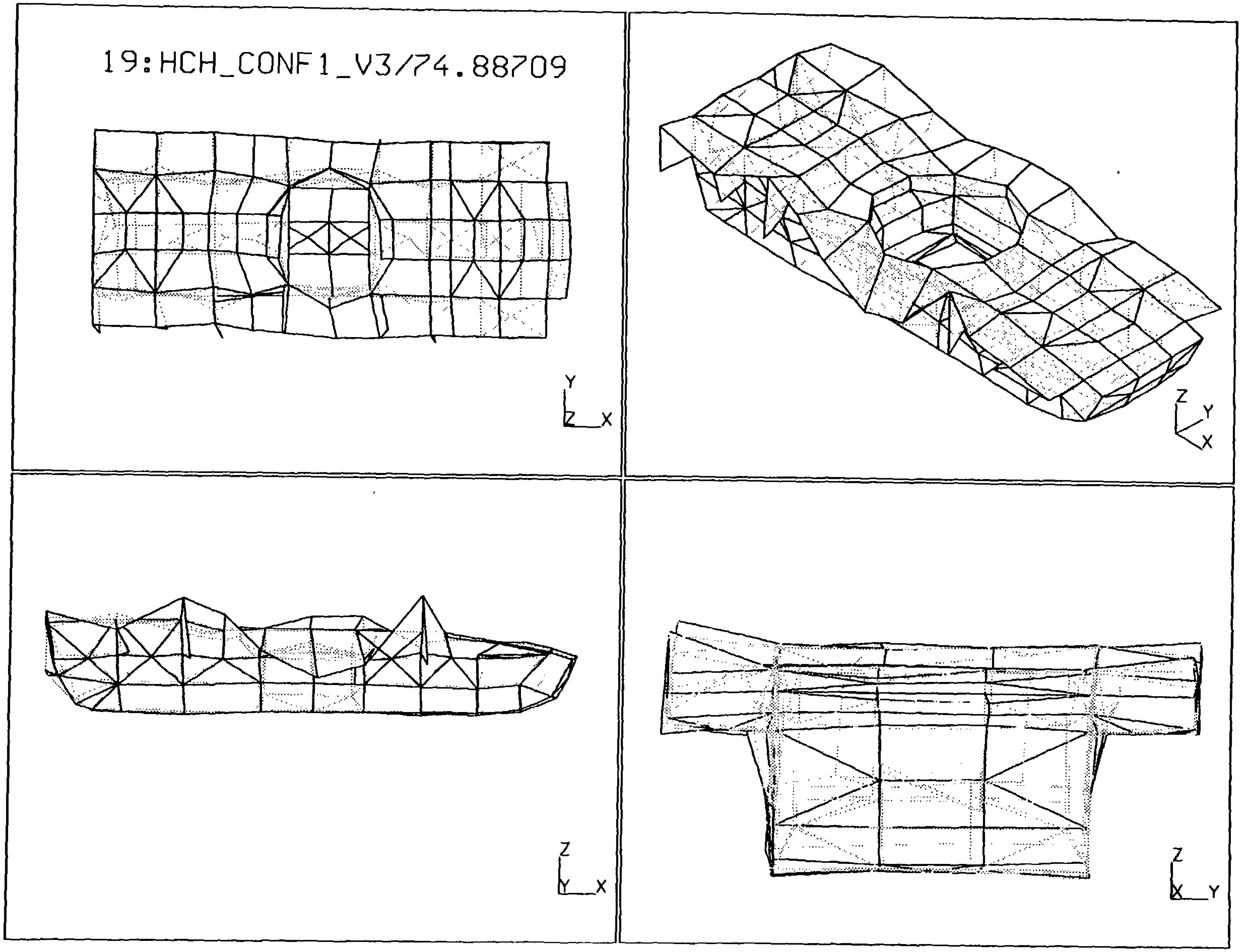

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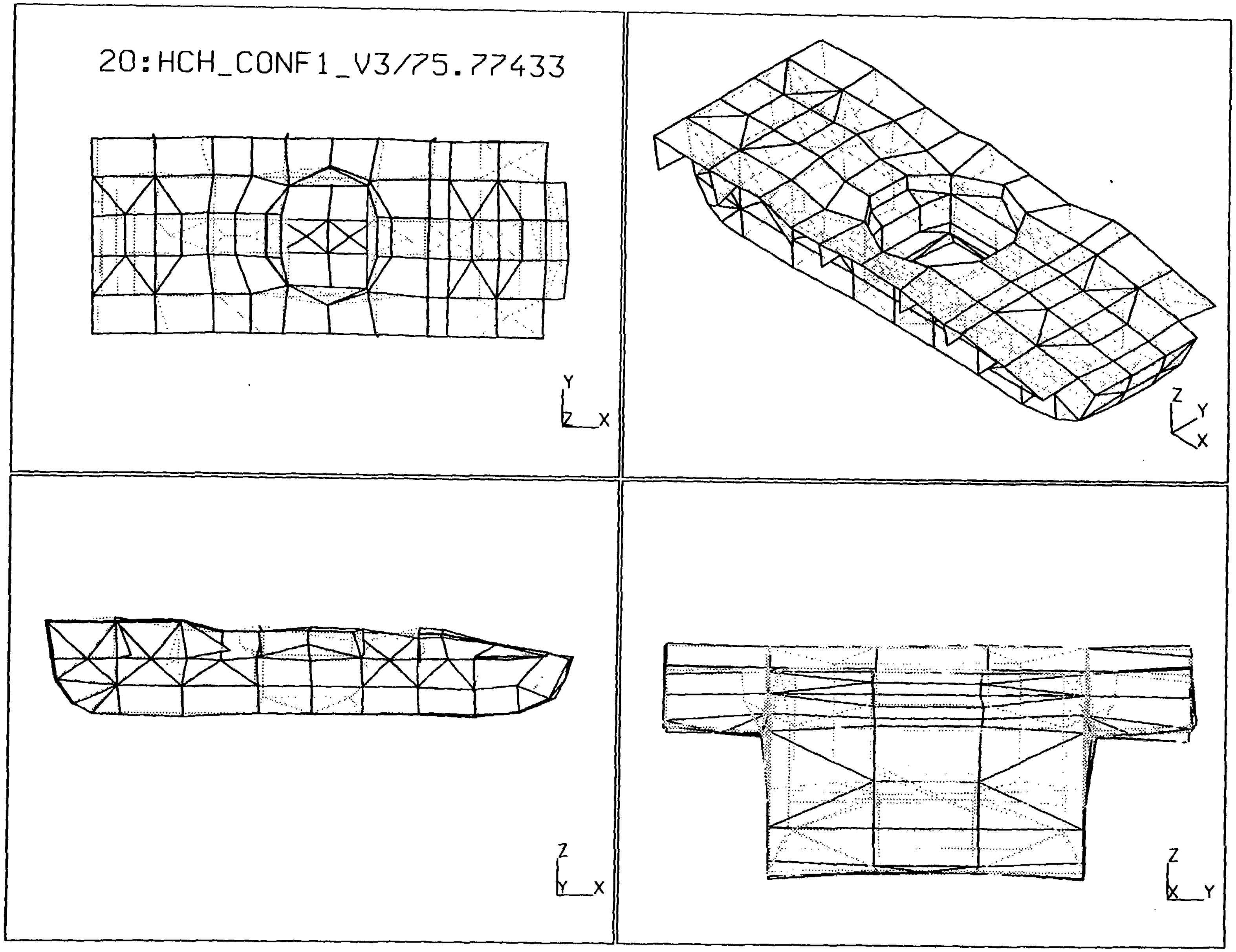

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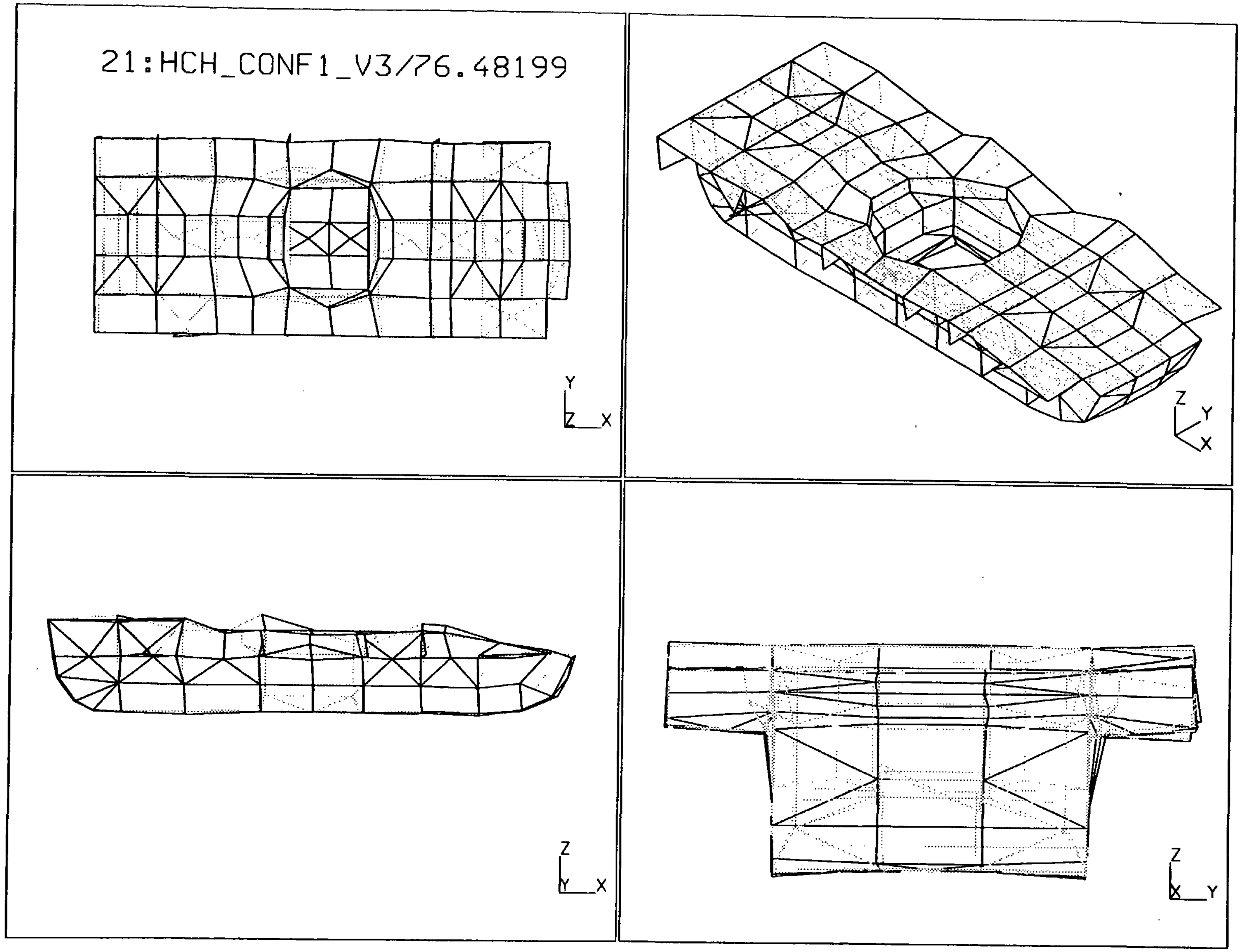

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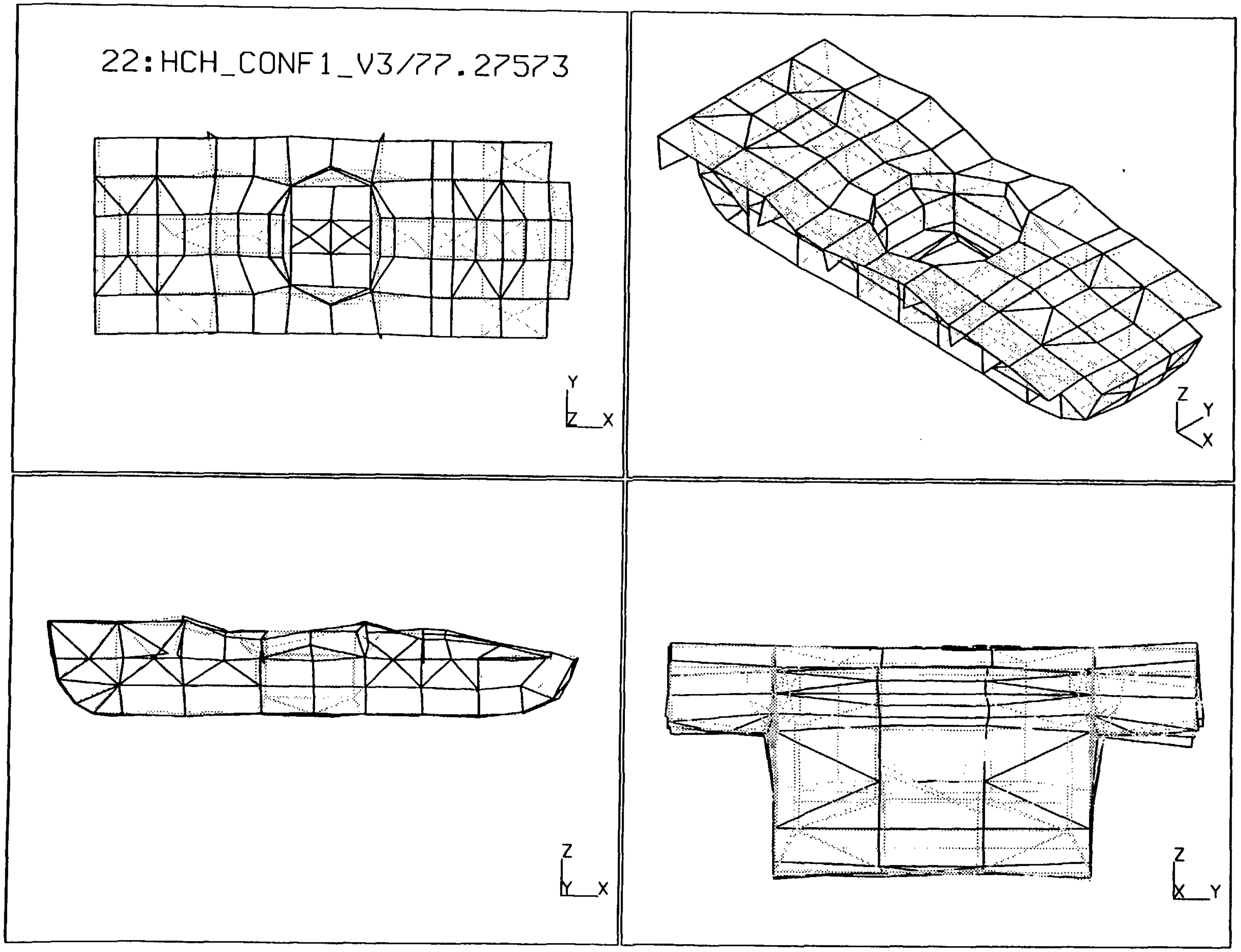

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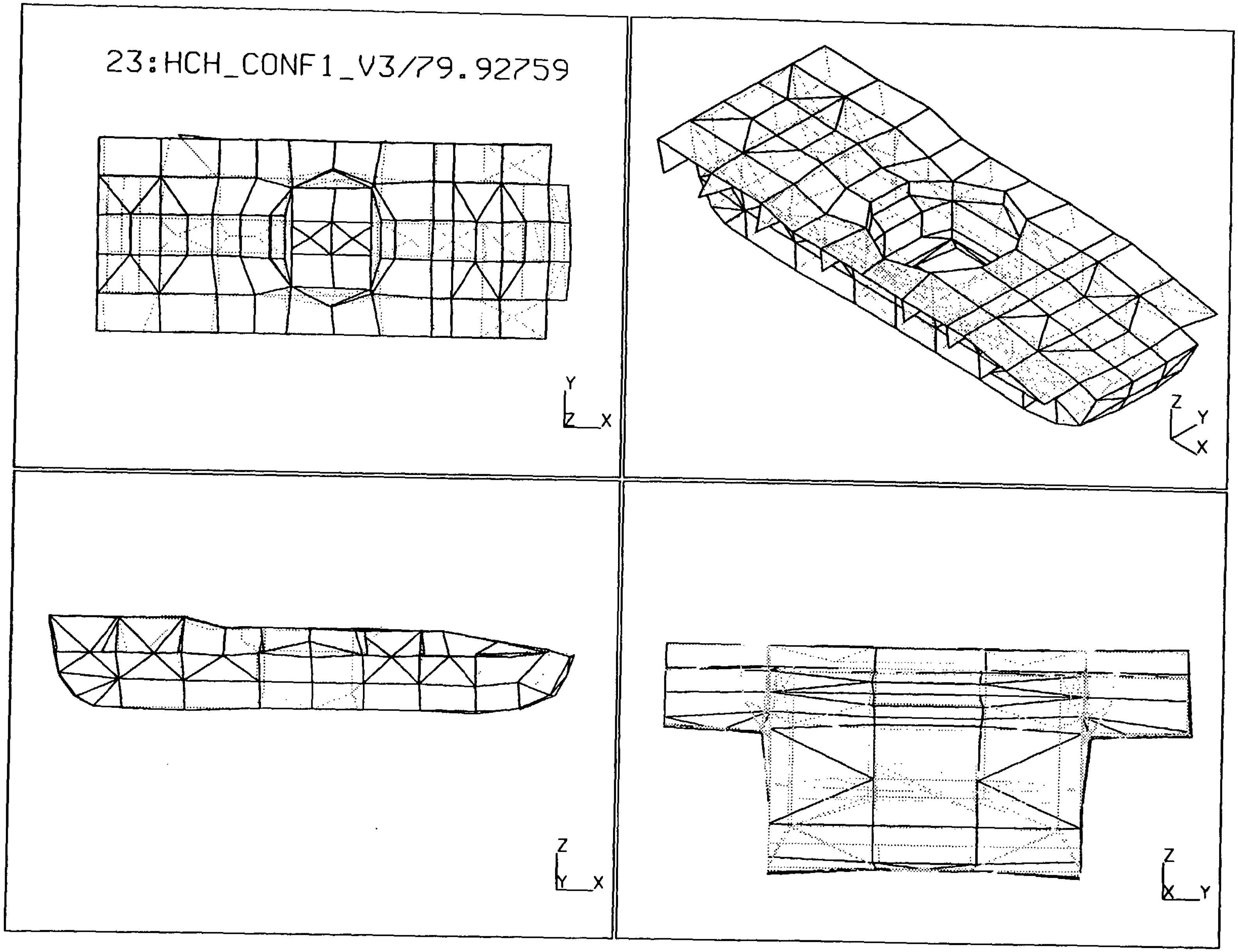

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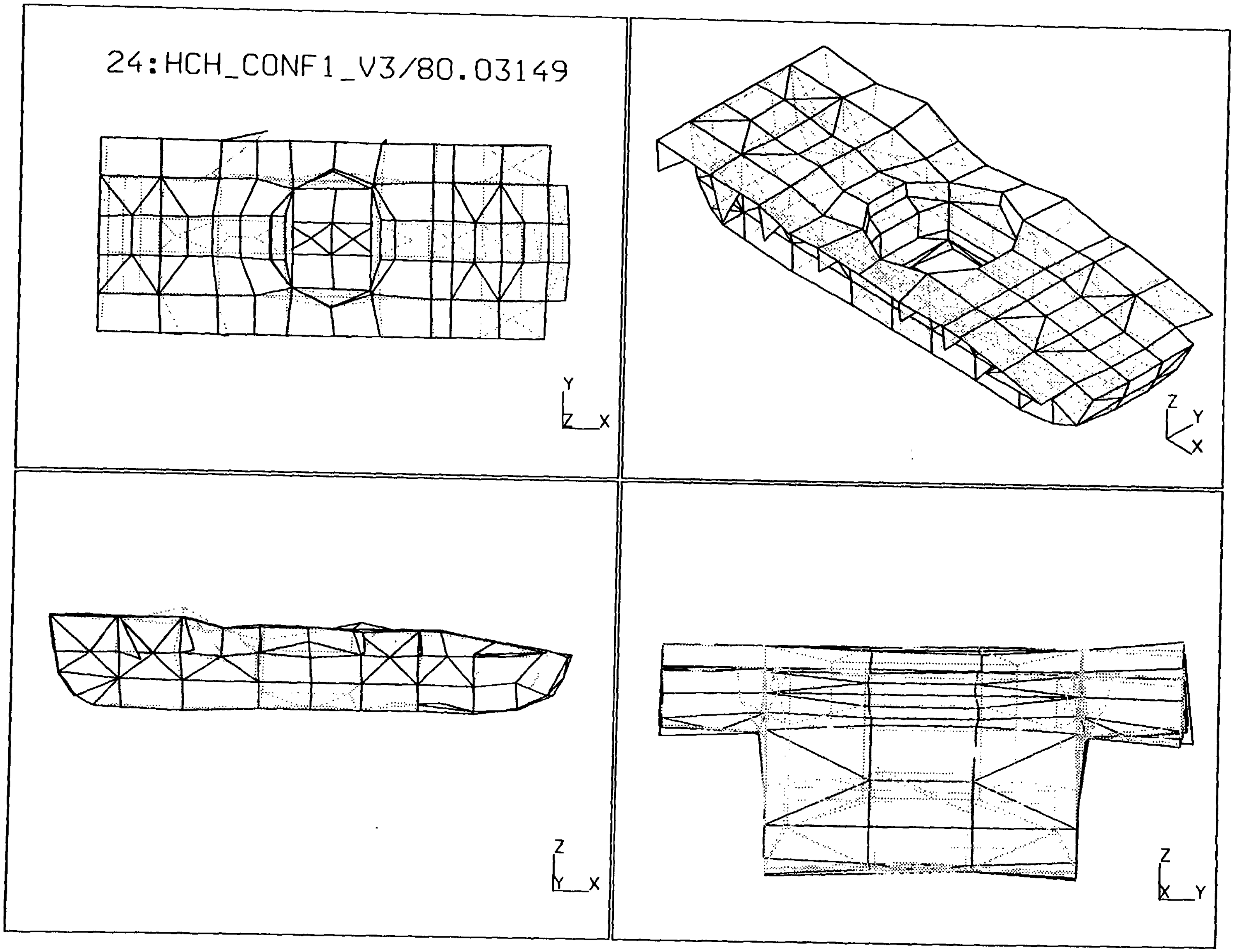

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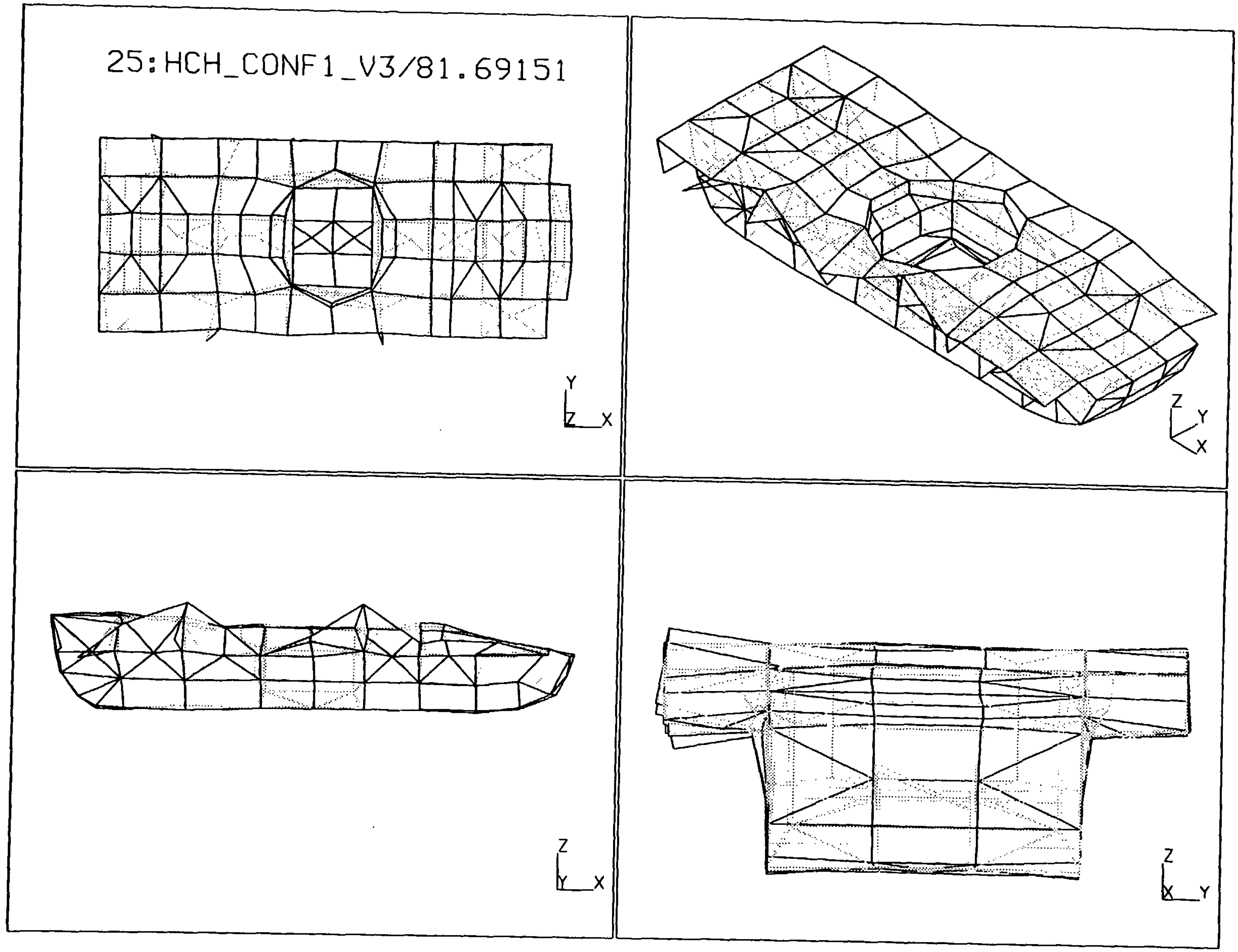

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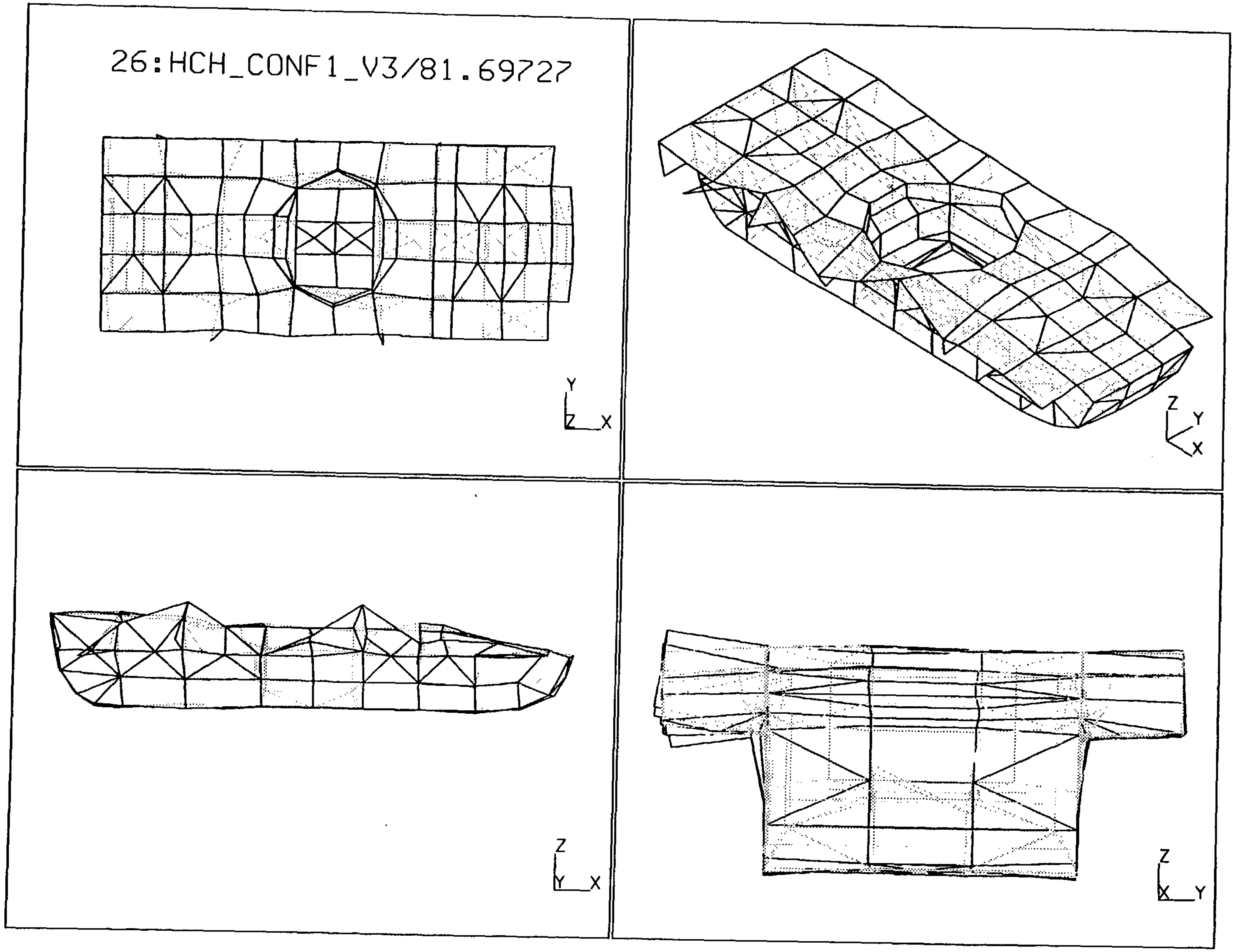

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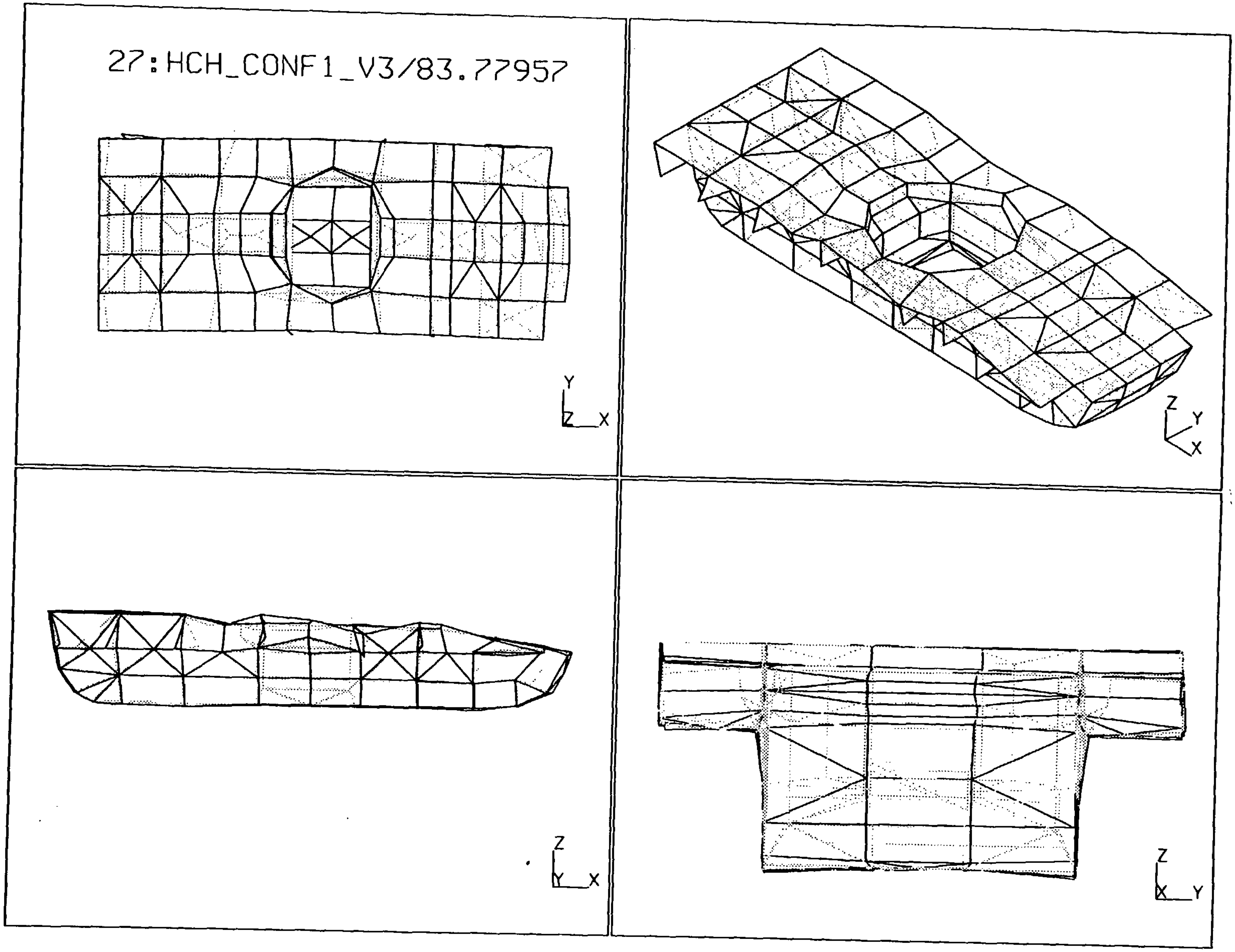

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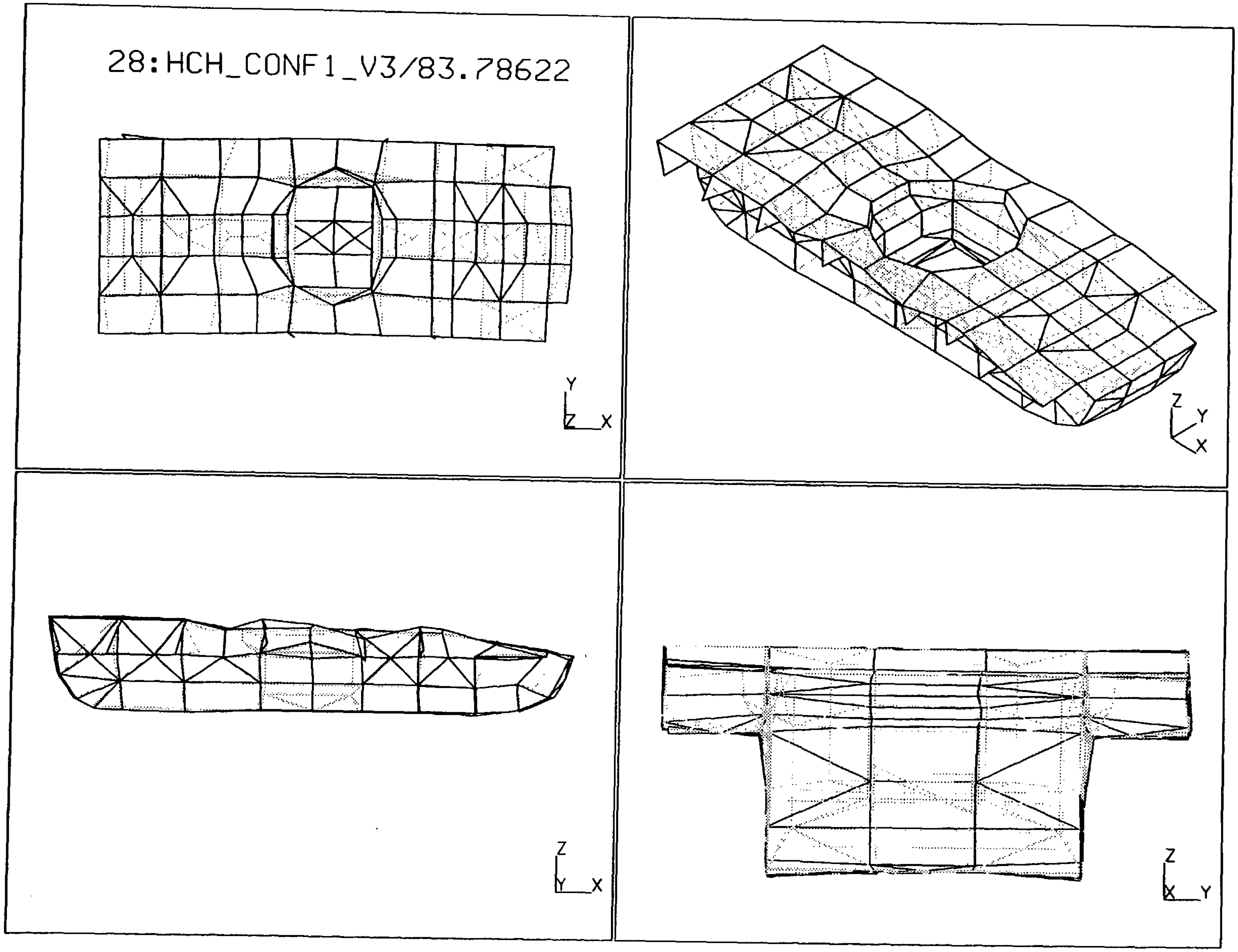

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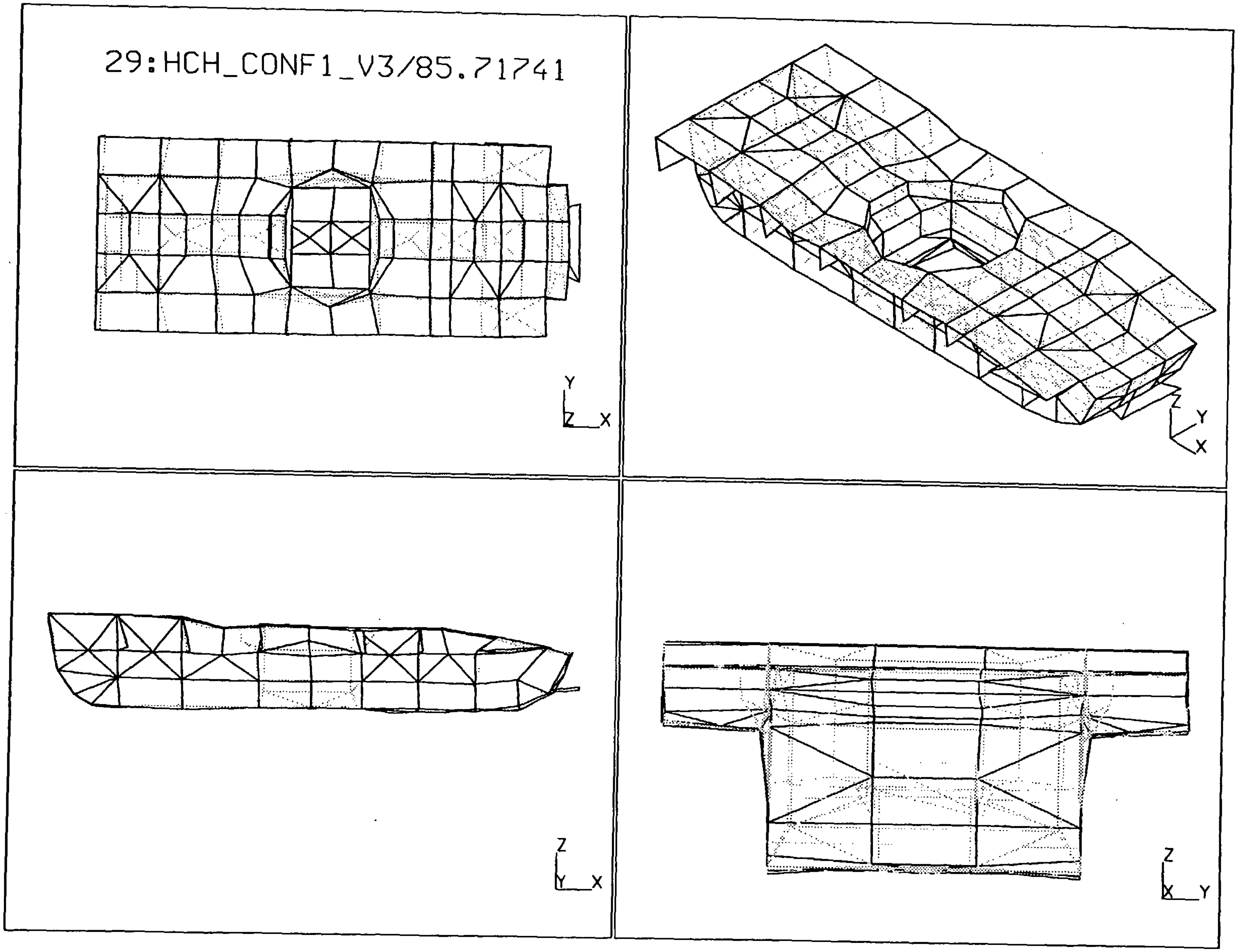

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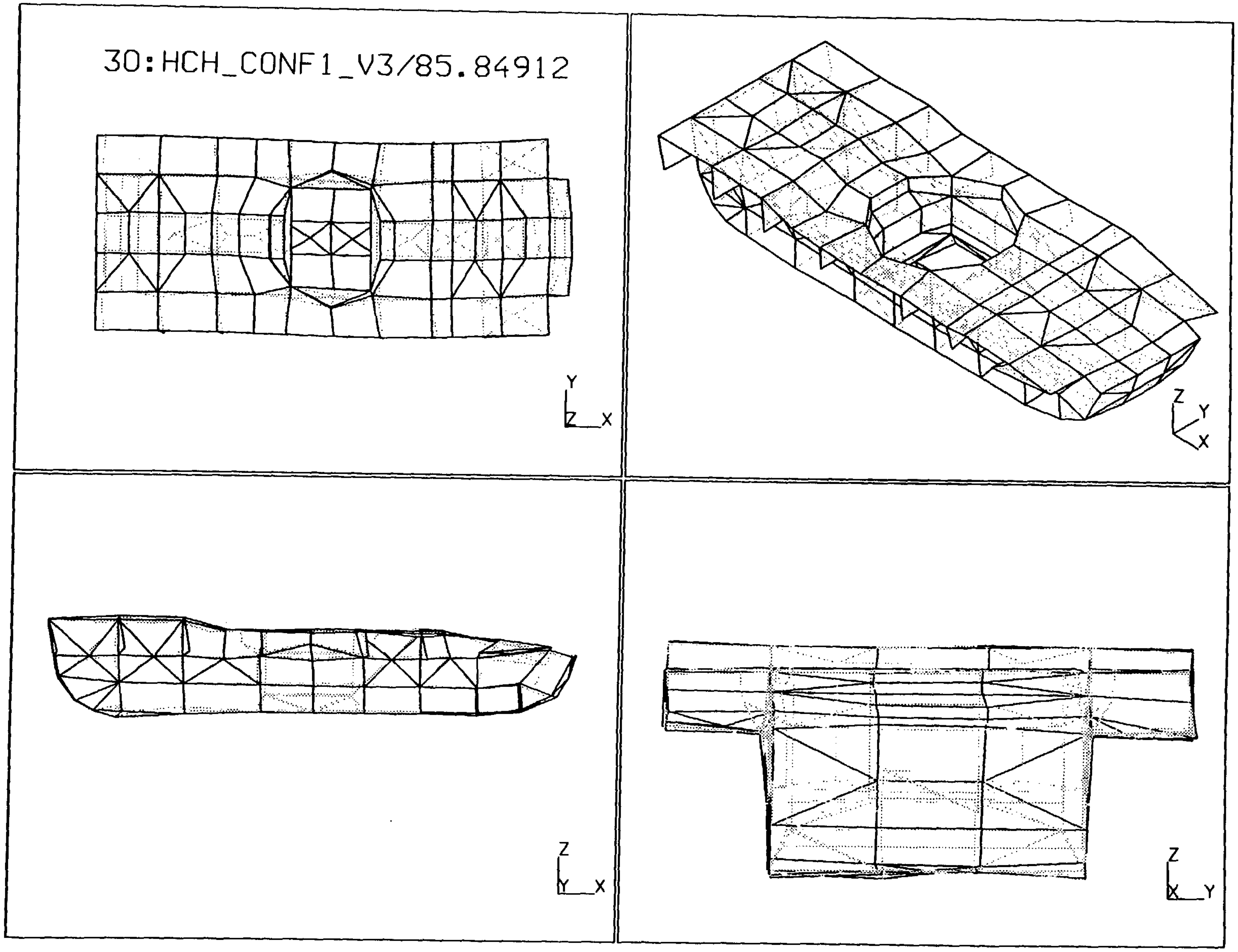

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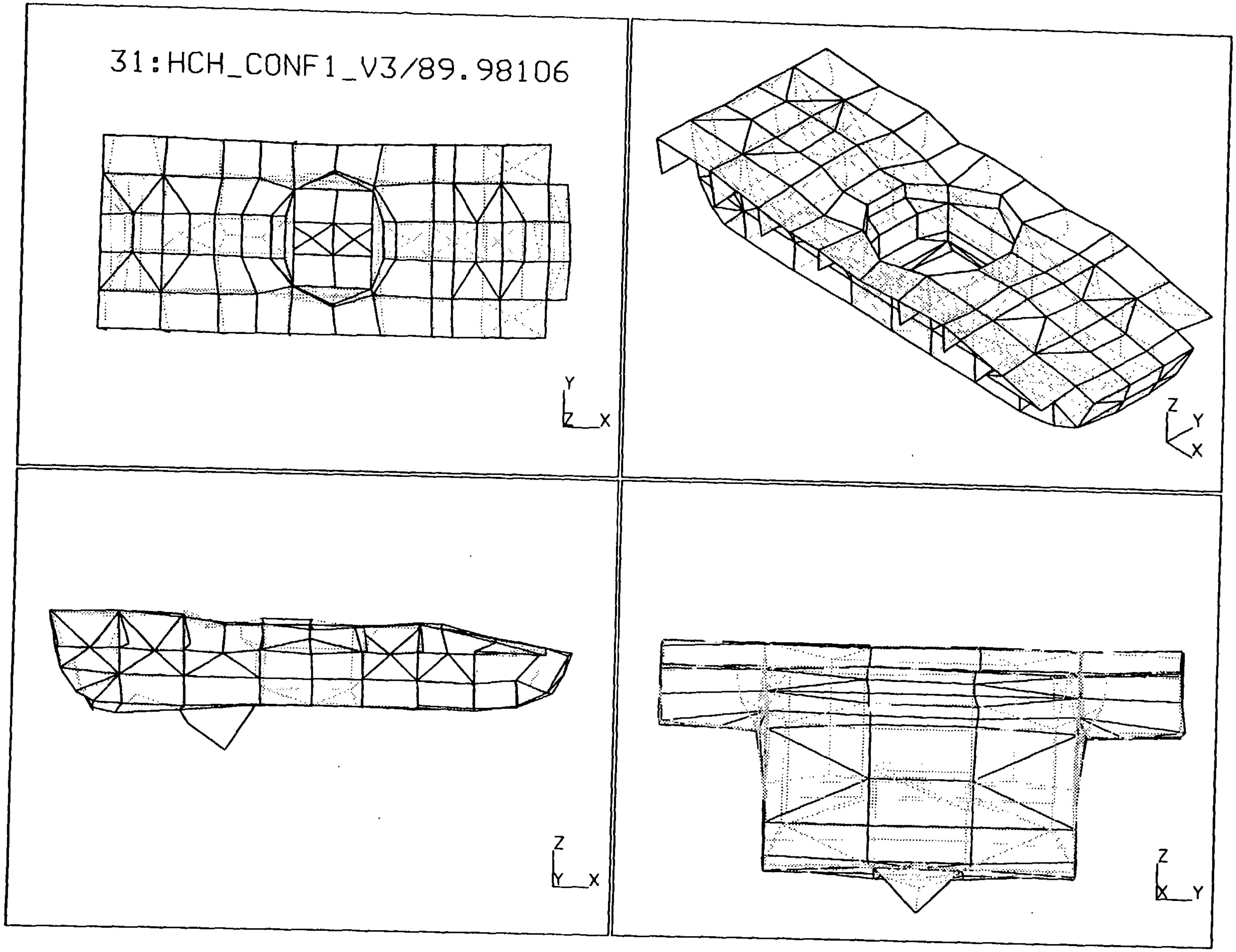

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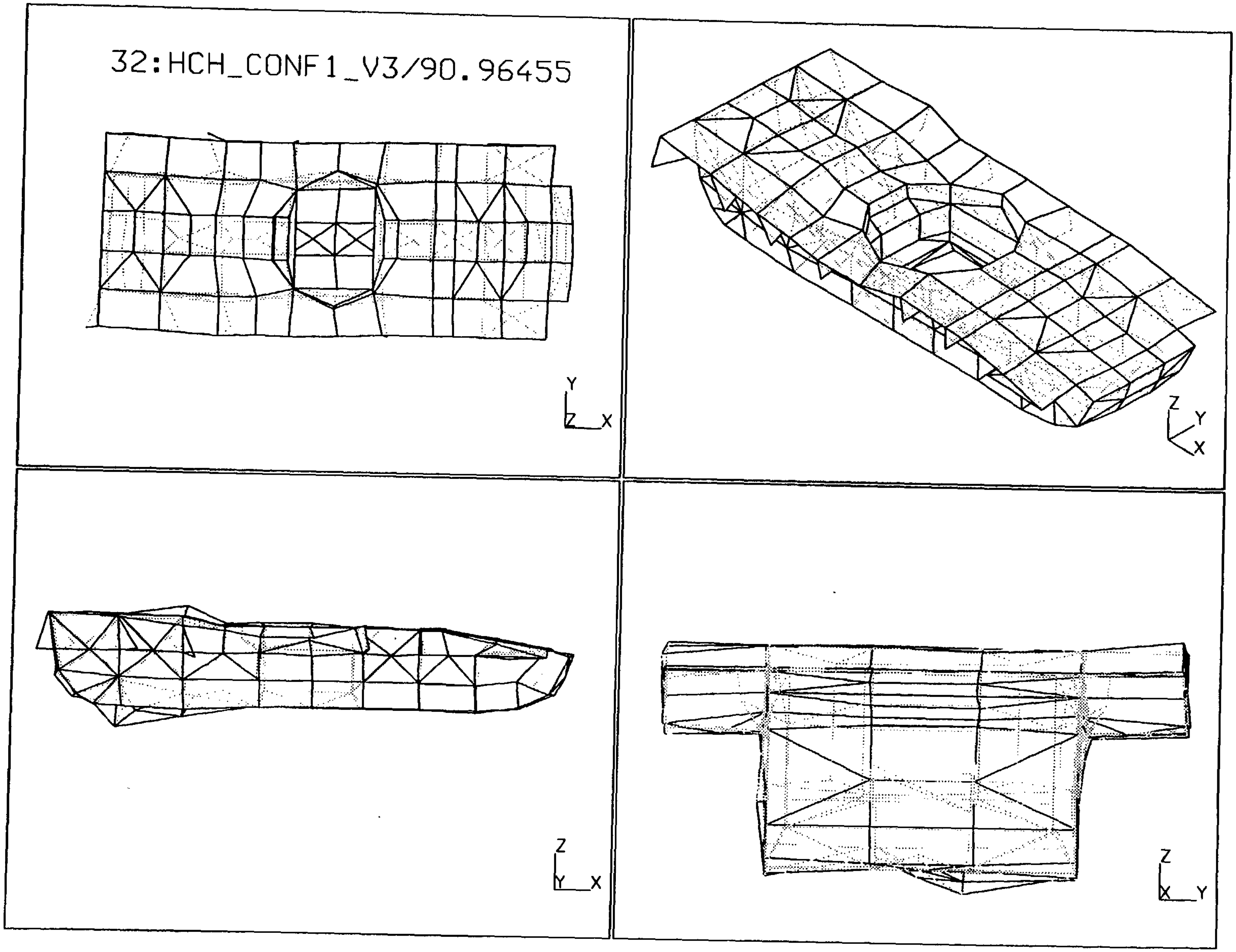

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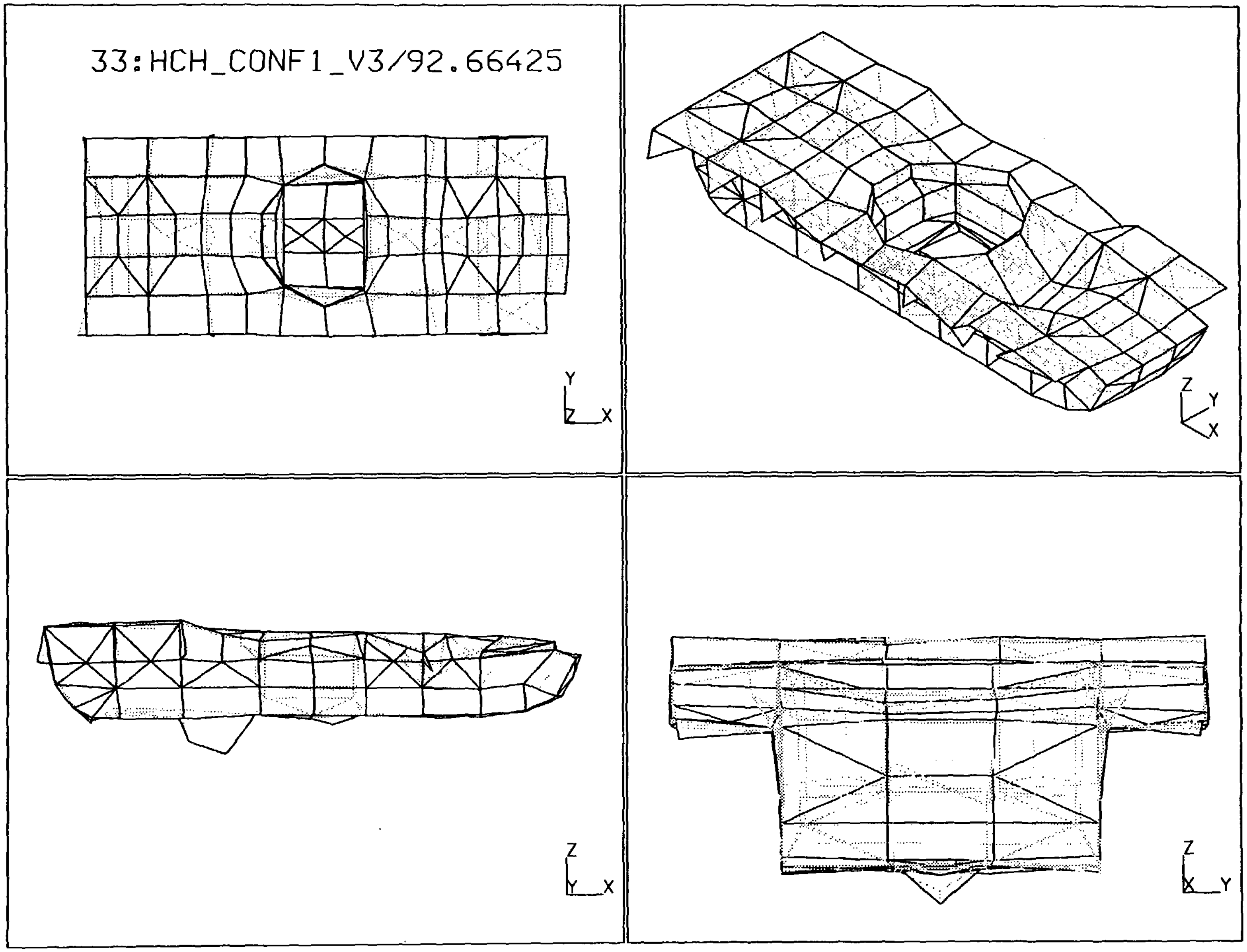

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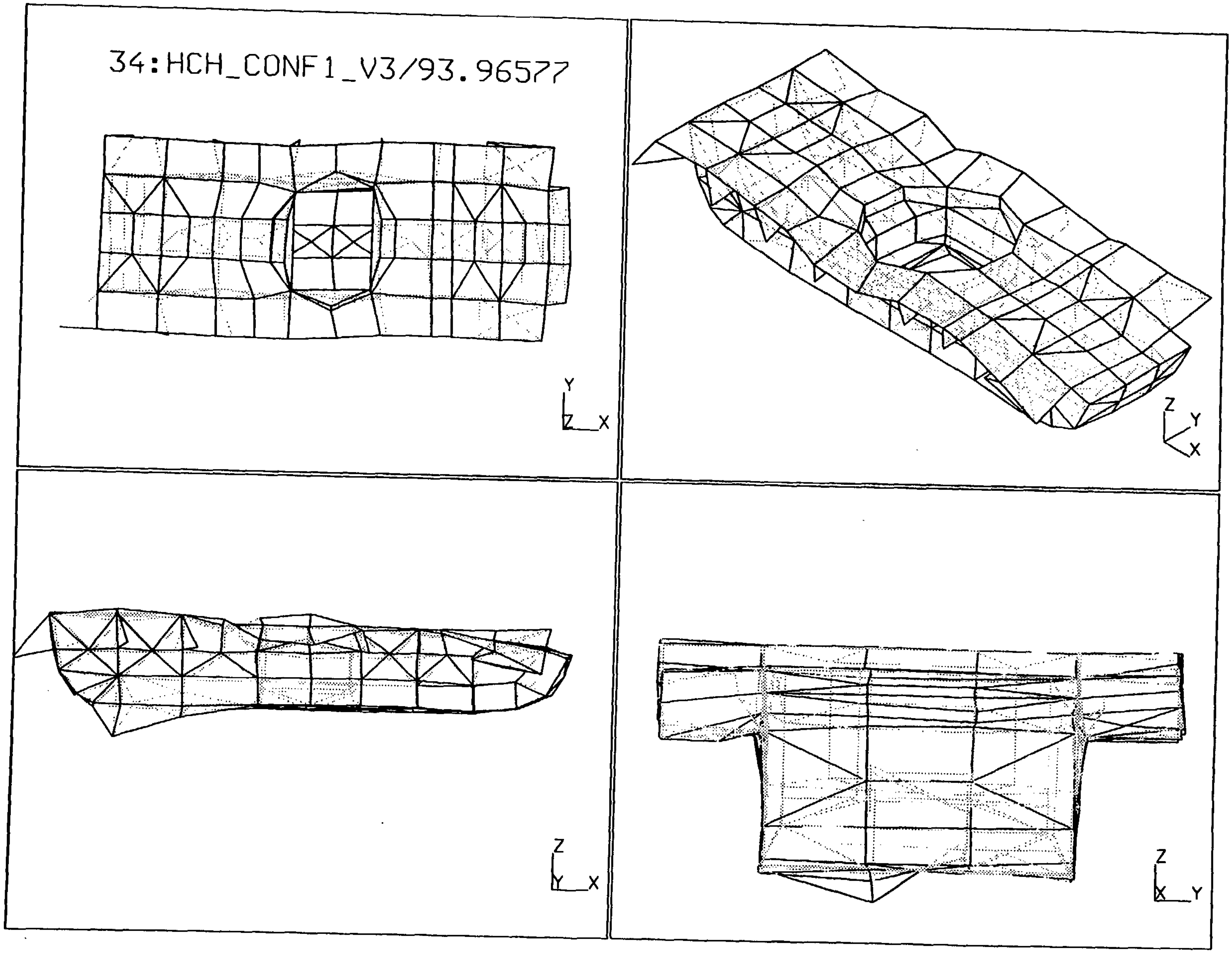

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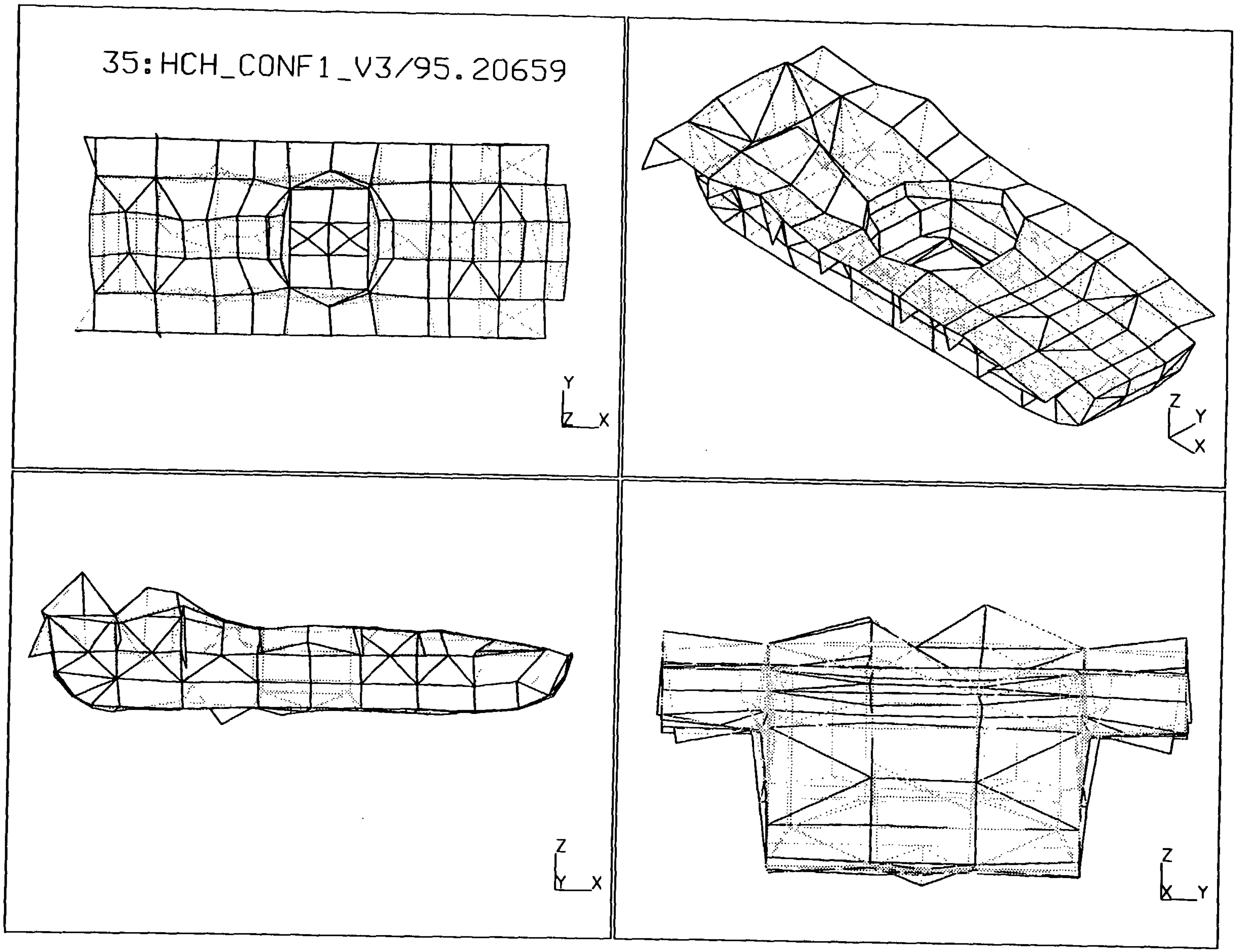

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Appendix C:

Heavy Composite Hull (HCH) Configuration 2 Mode Shapes

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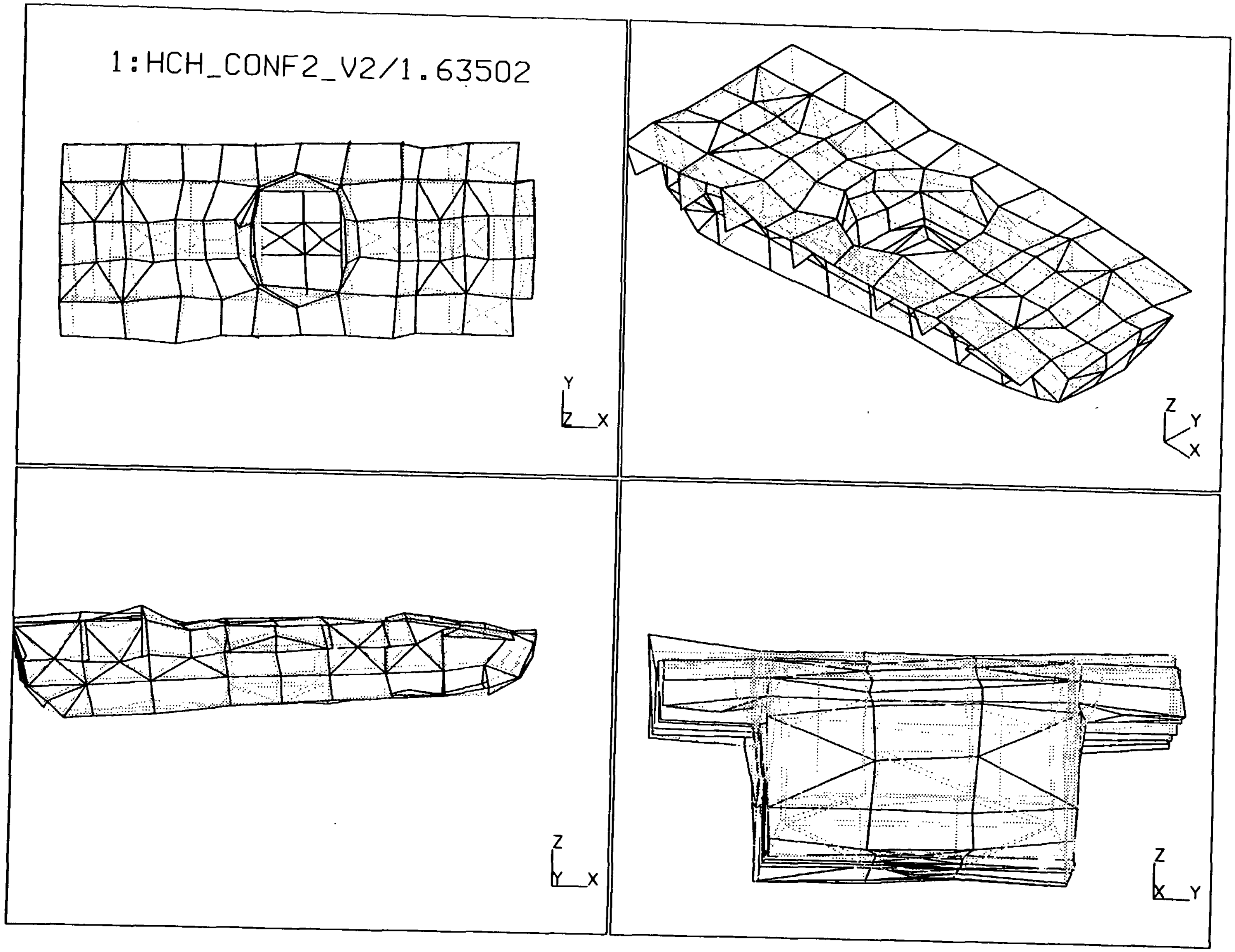

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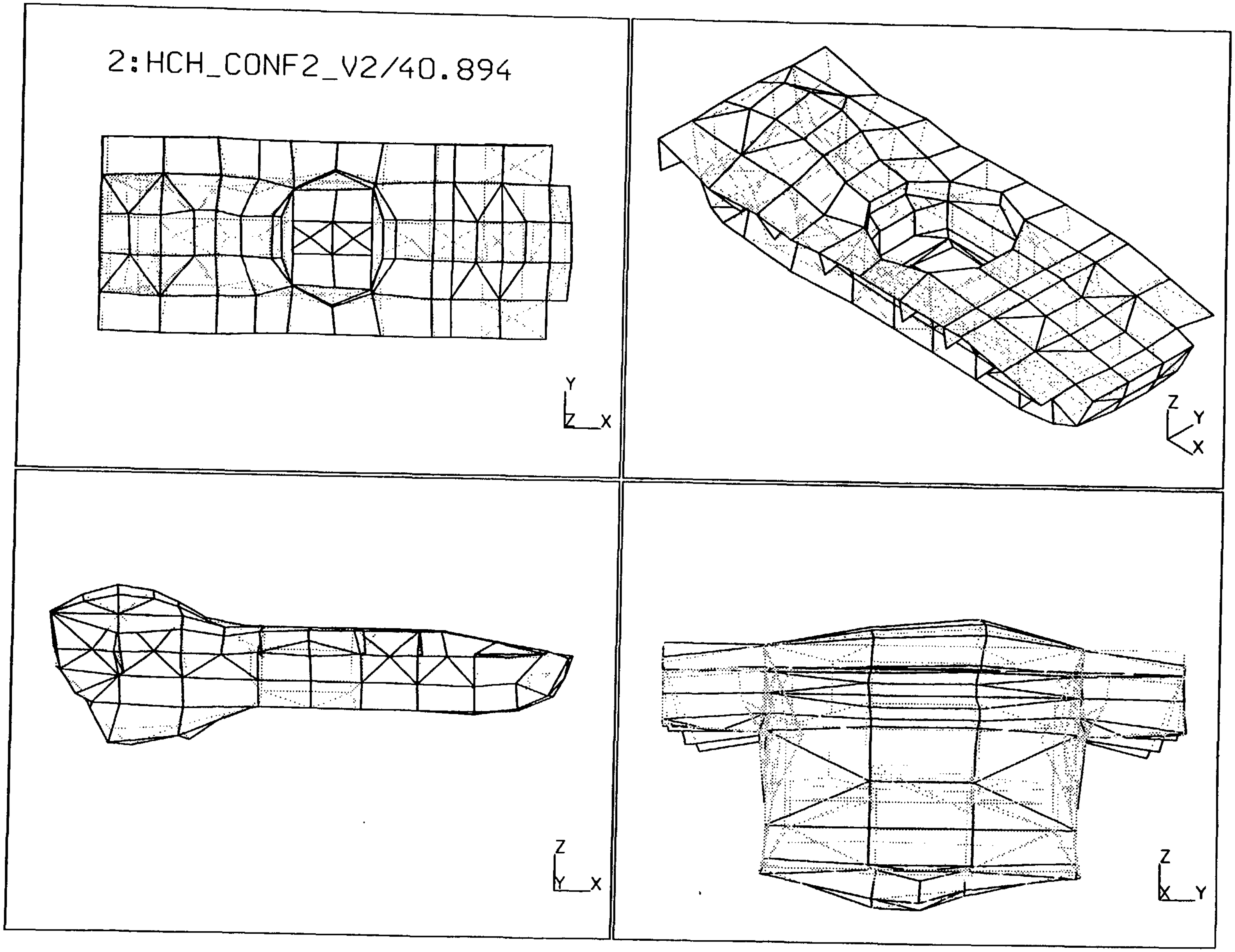

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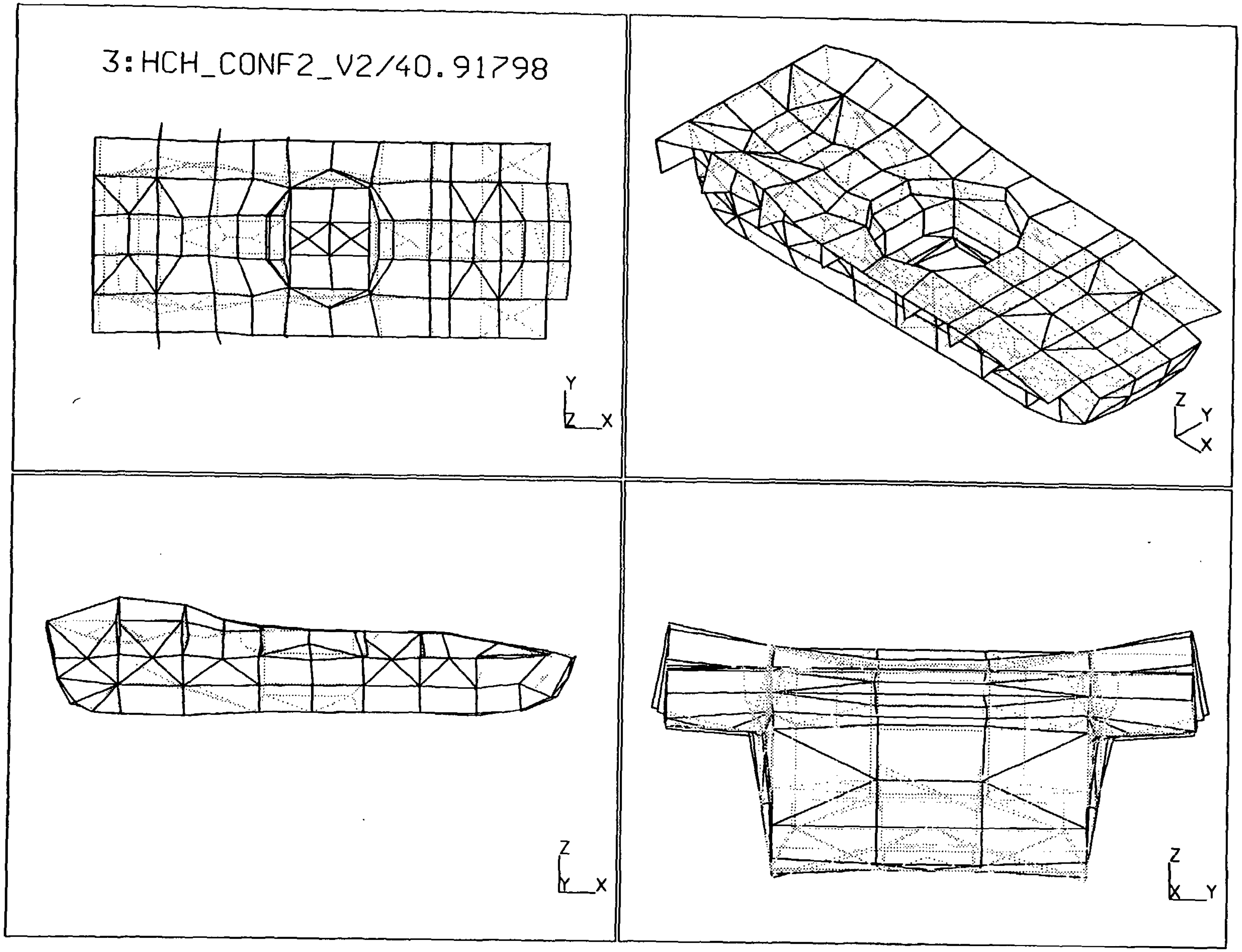

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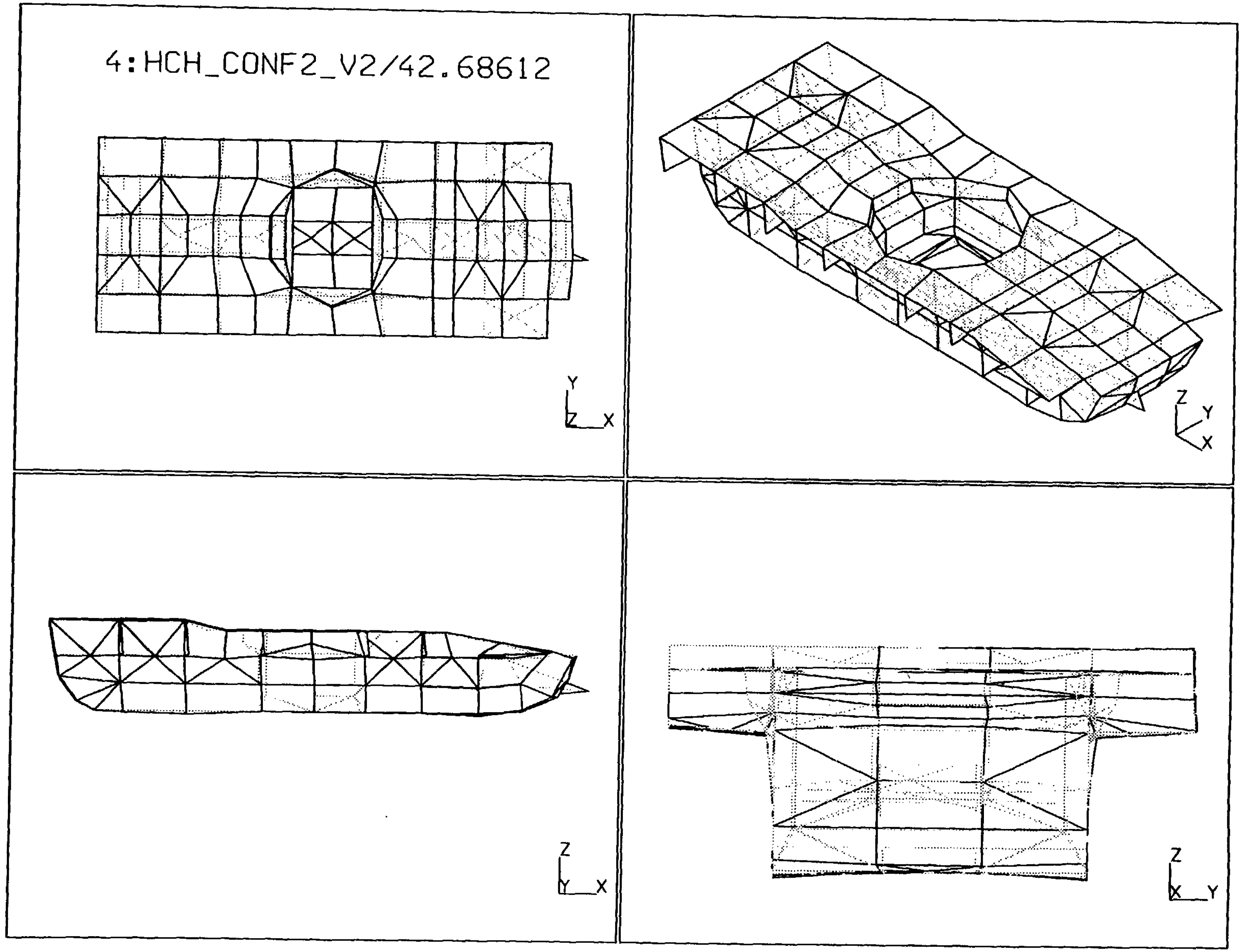

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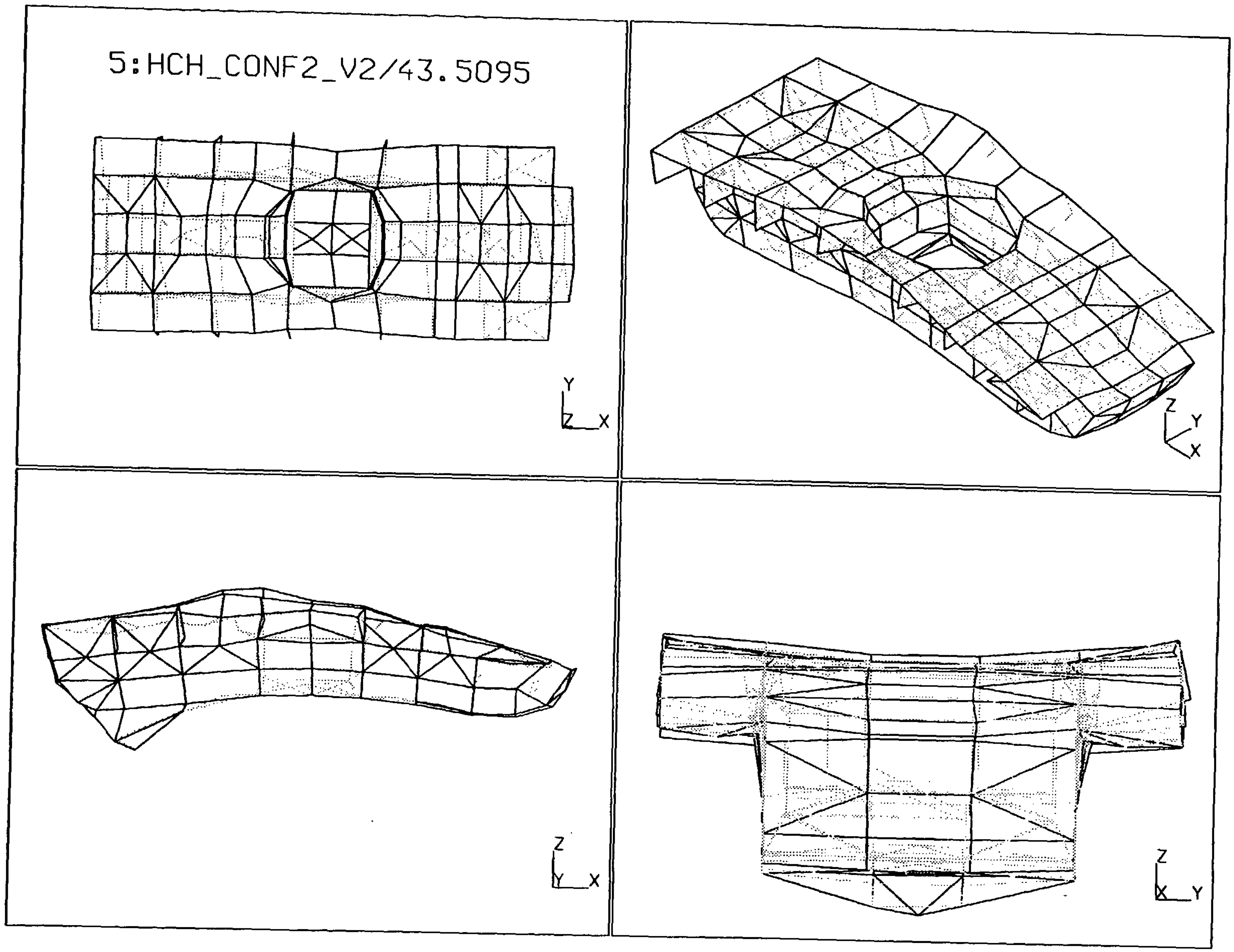

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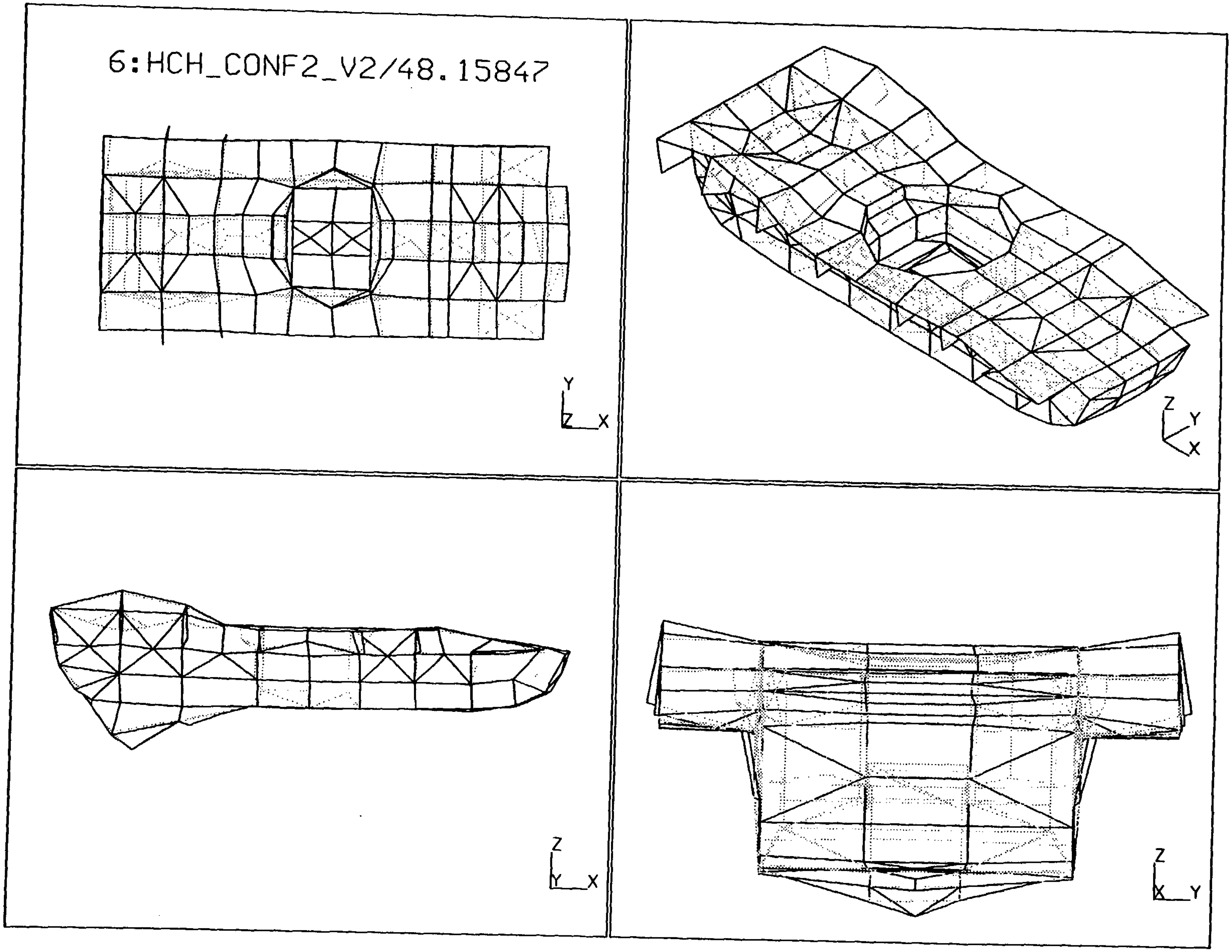

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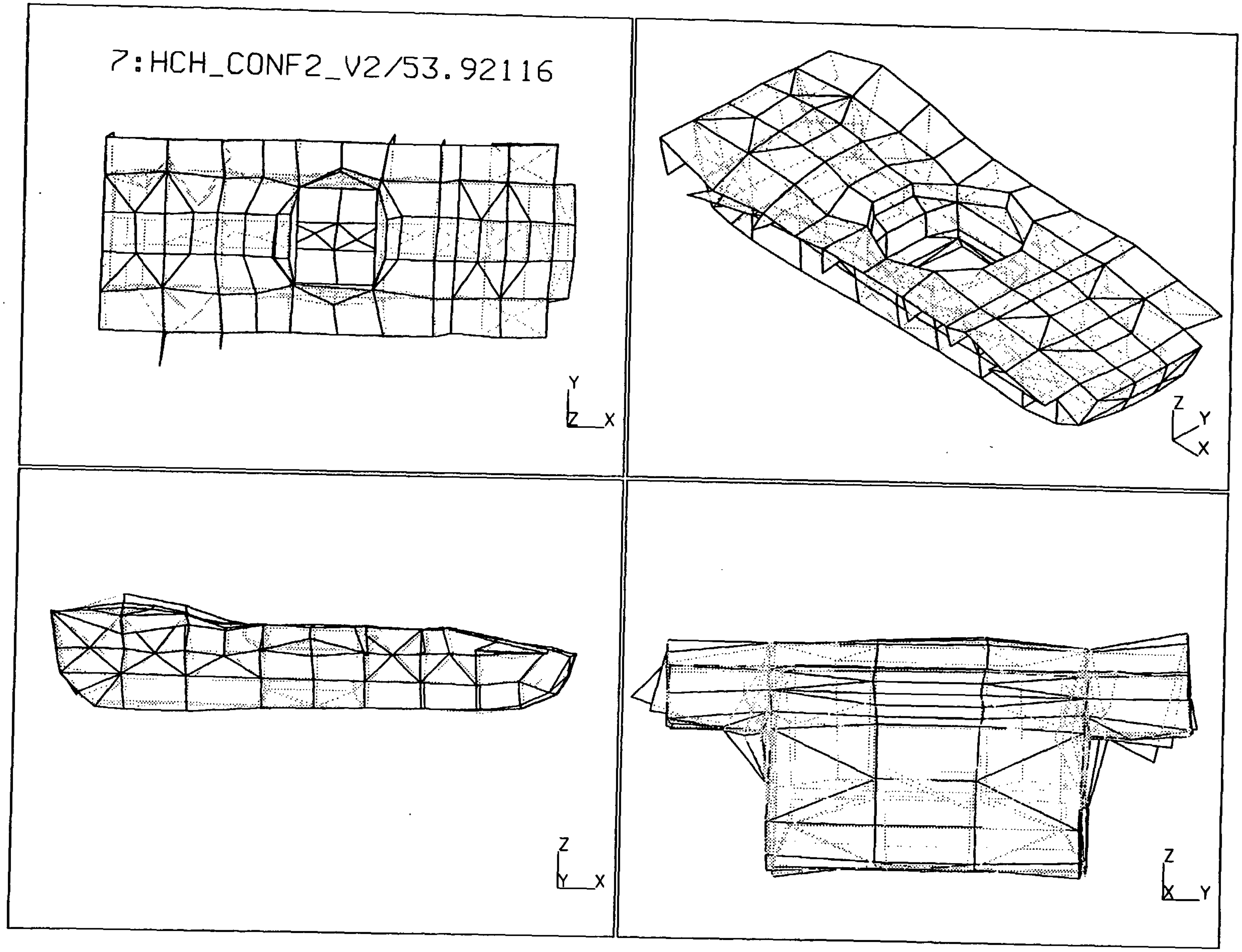

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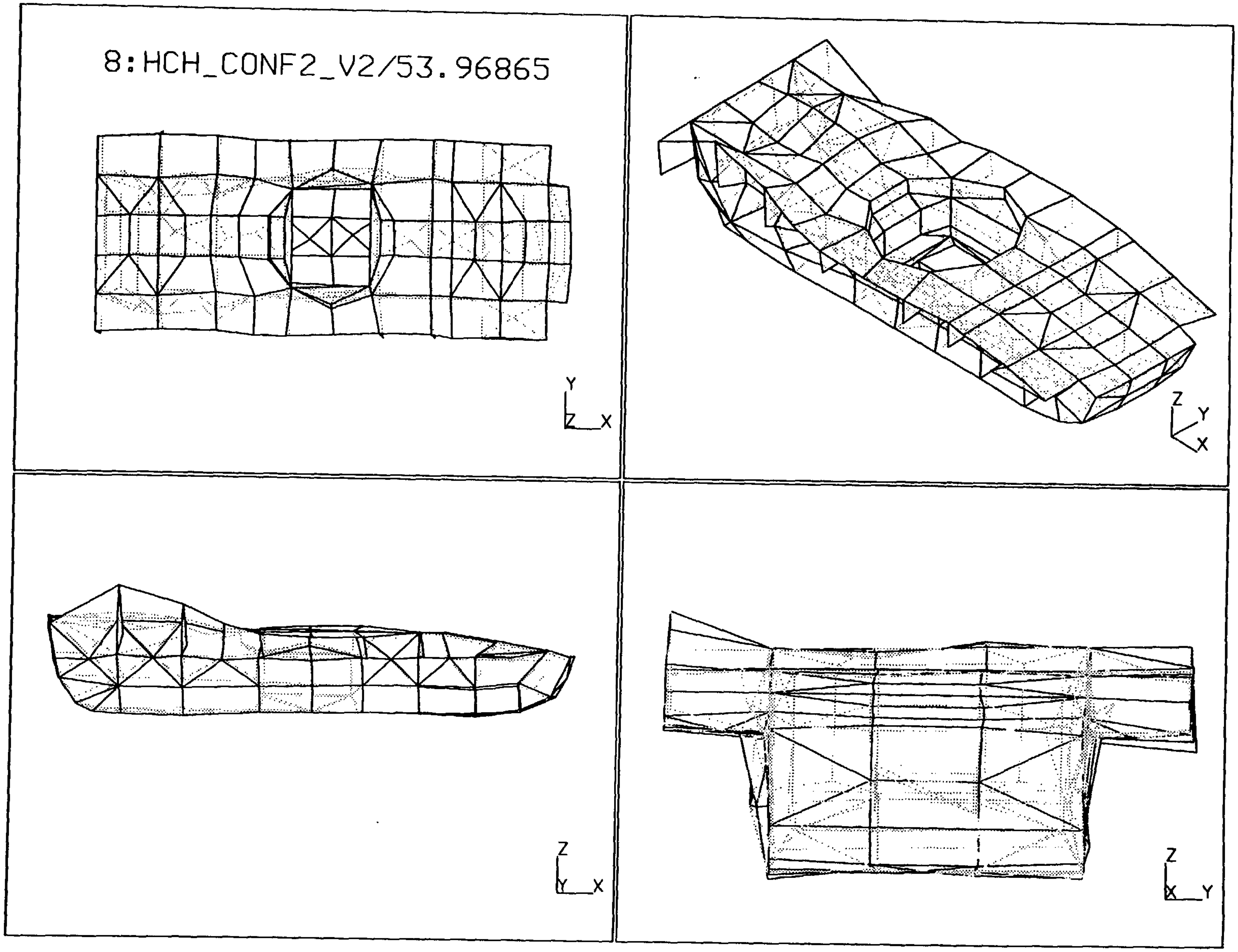

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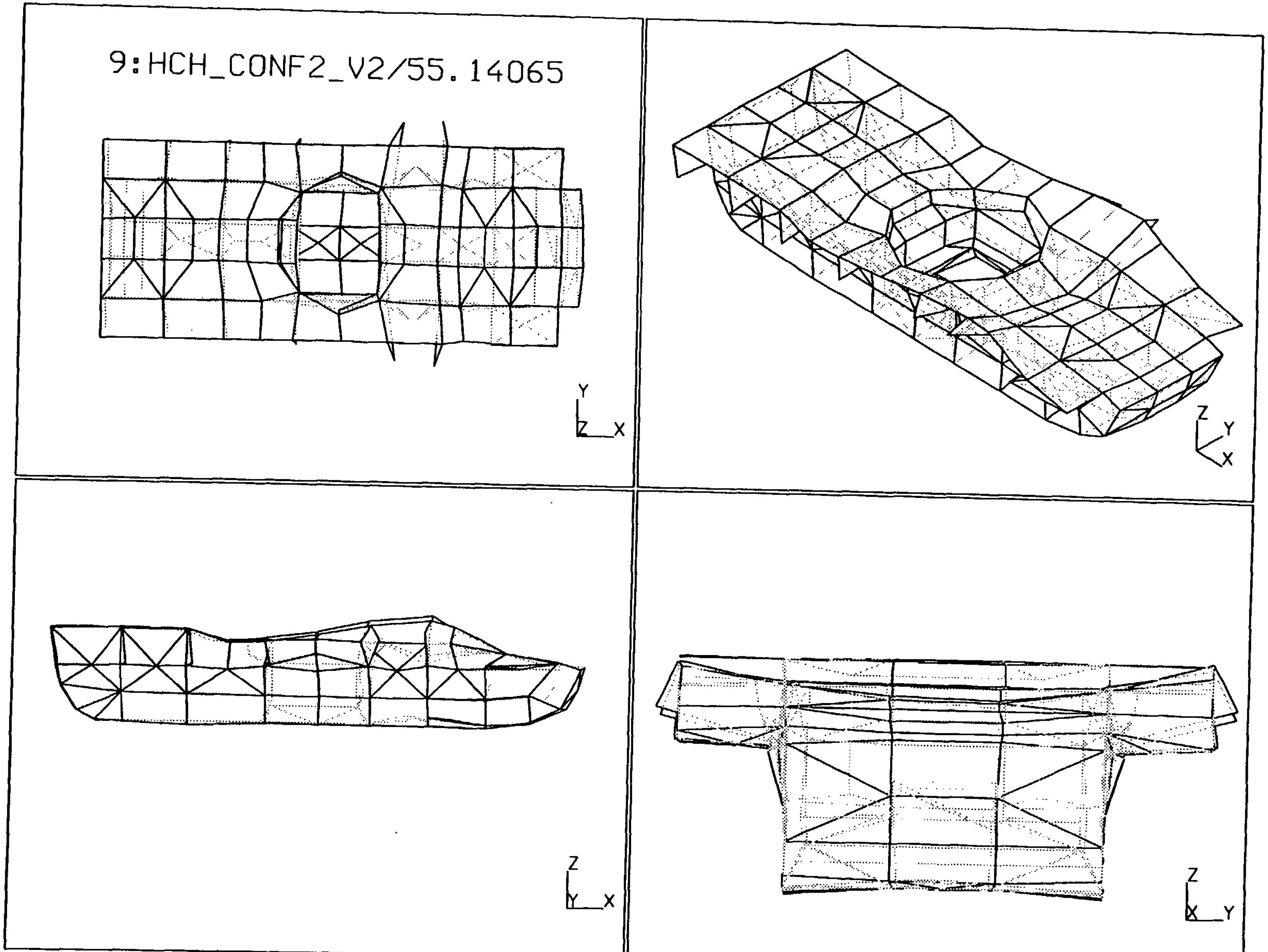

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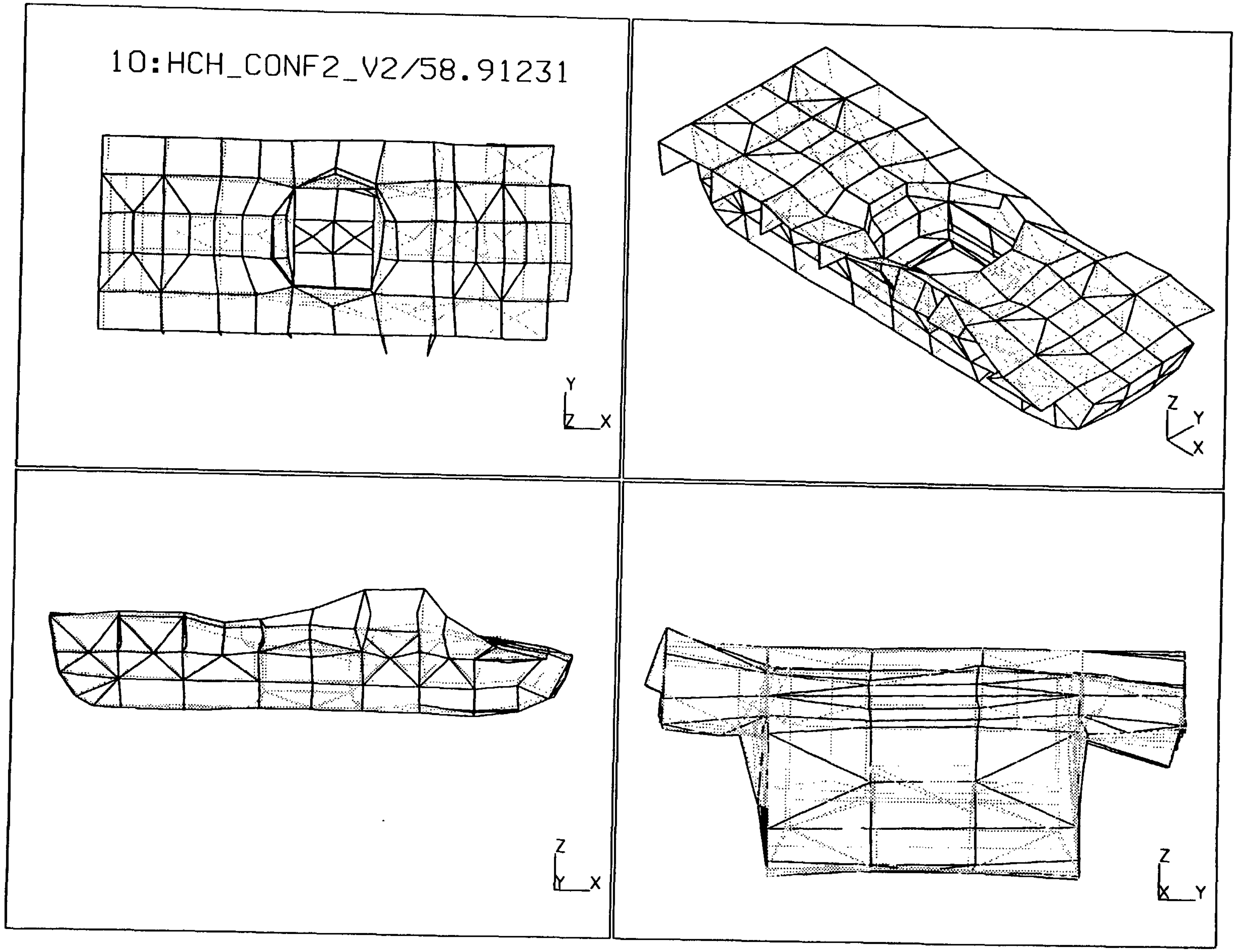

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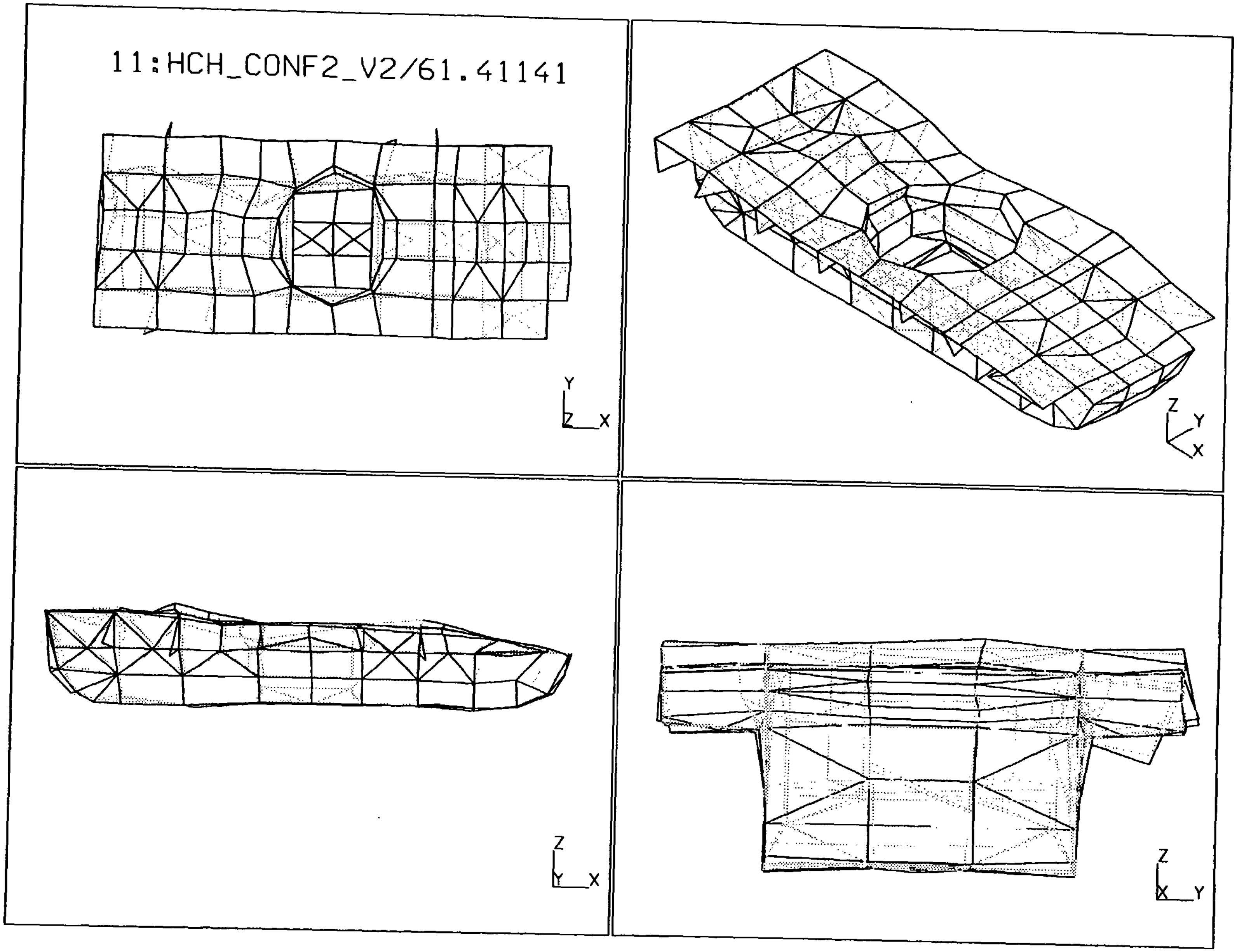

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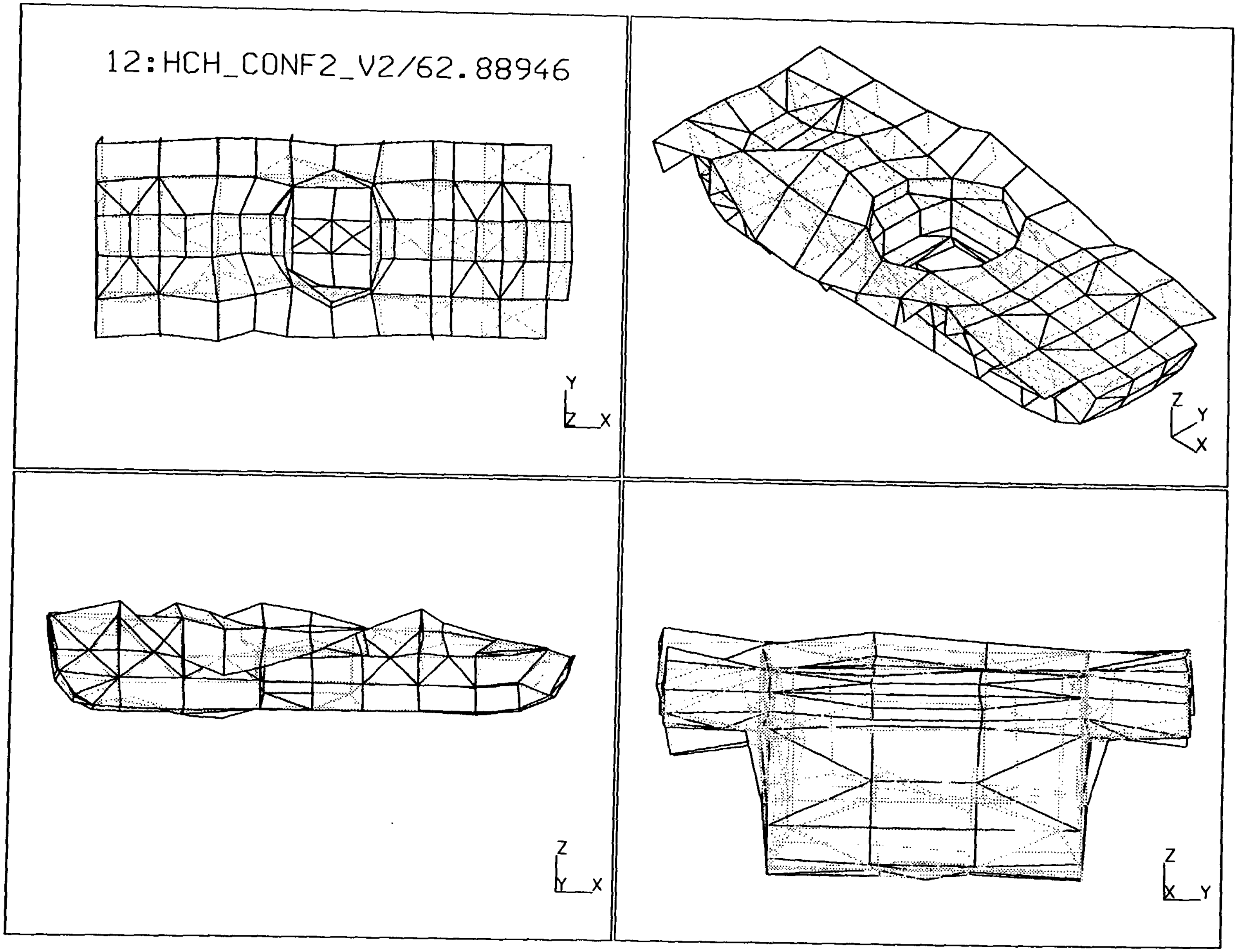

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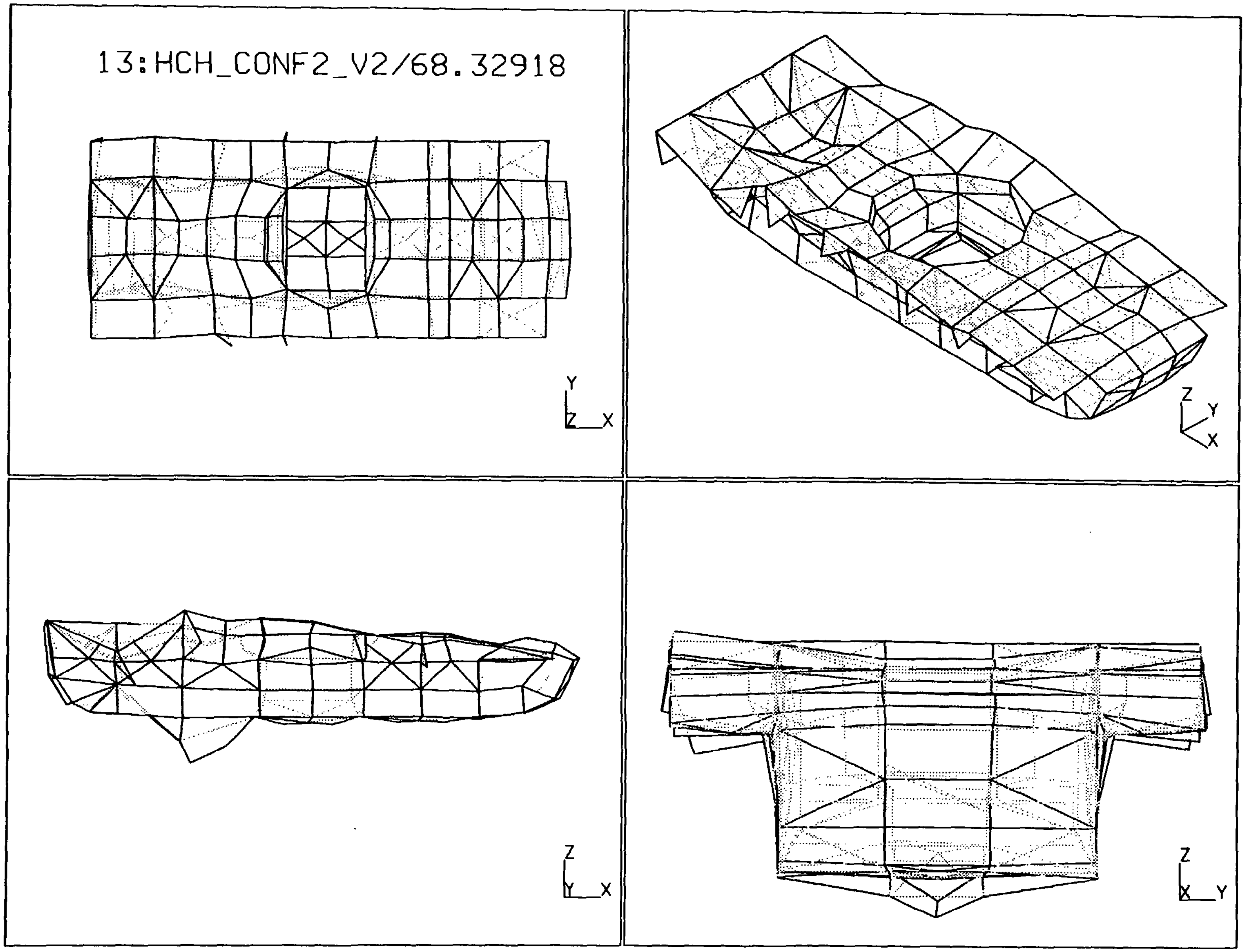

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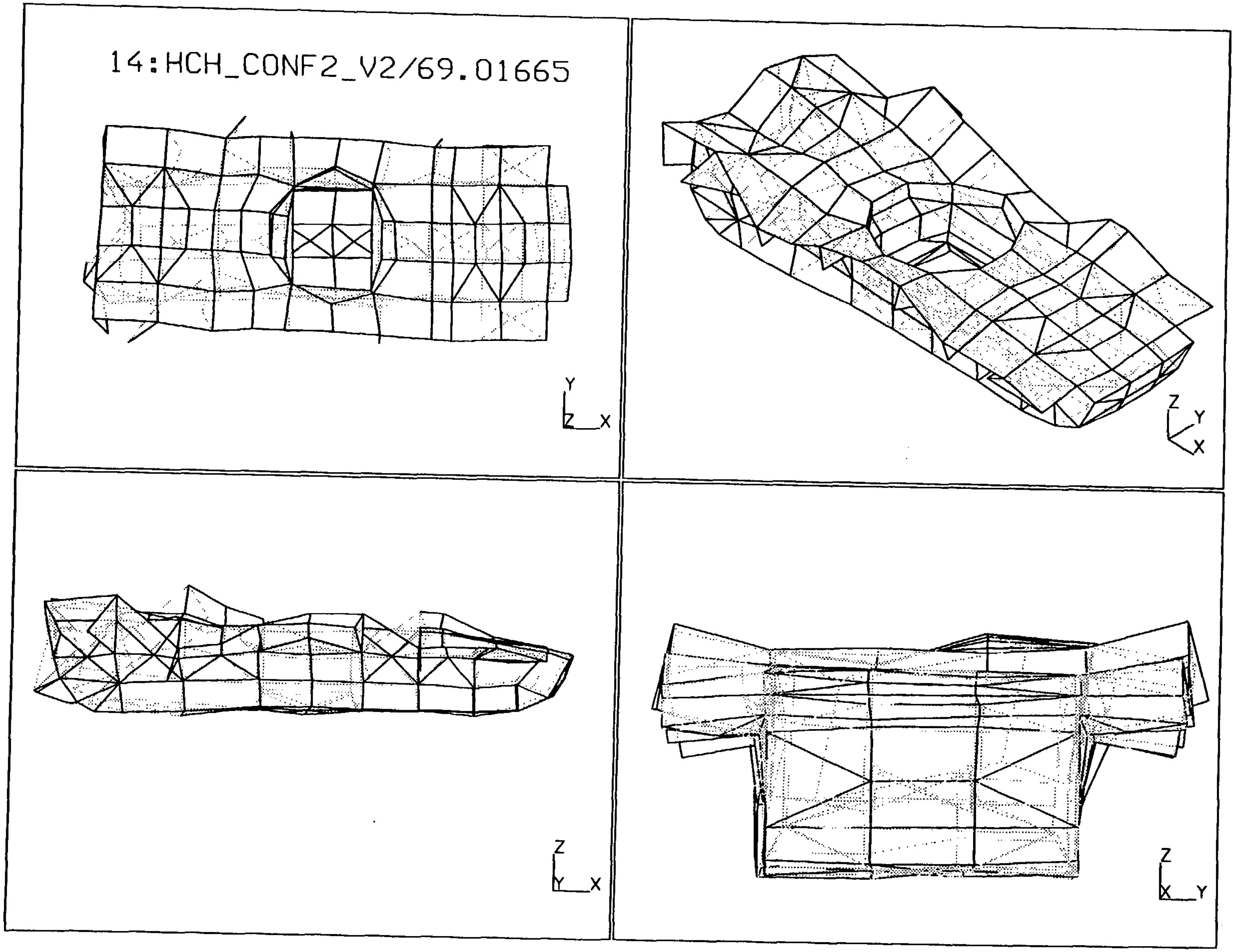

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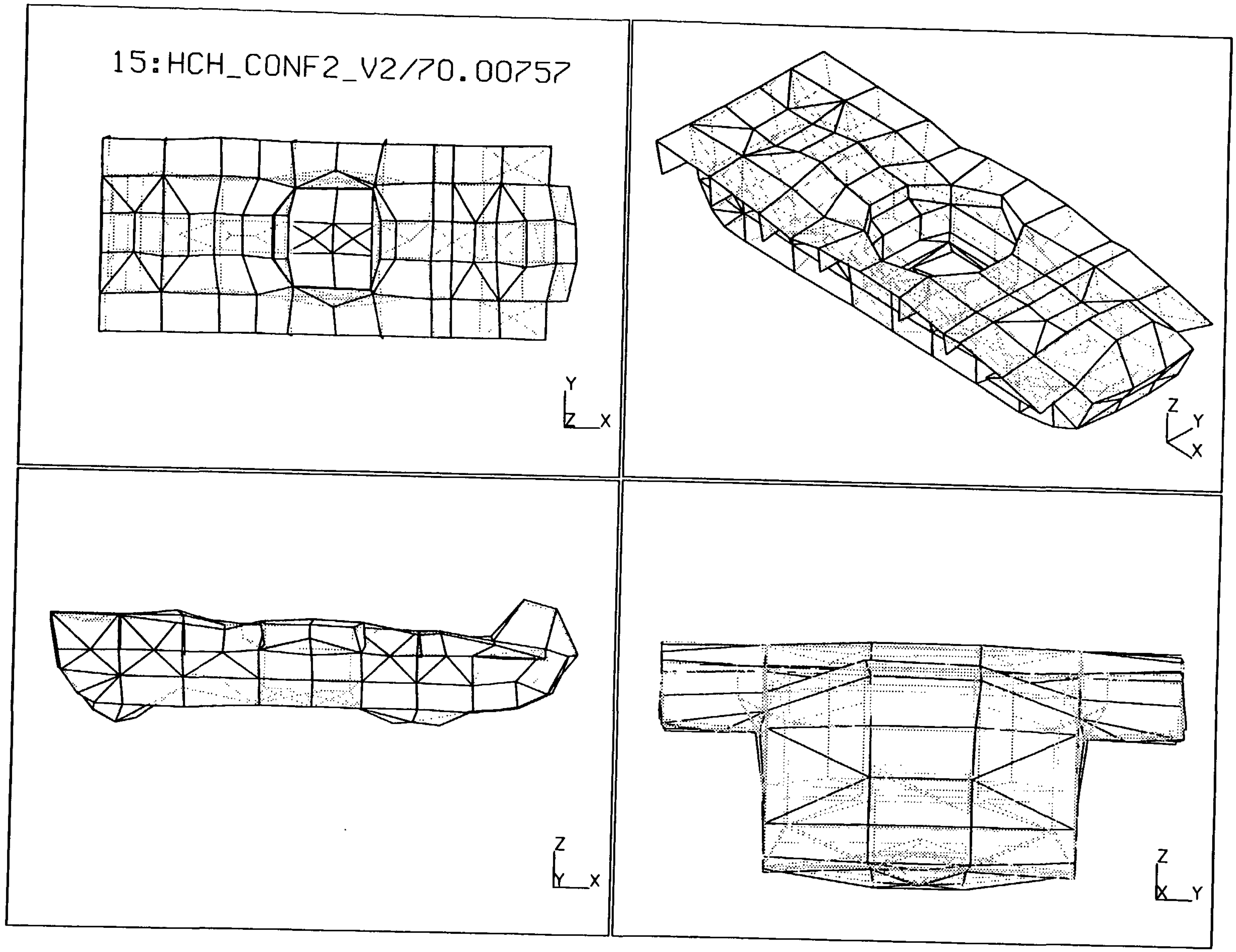

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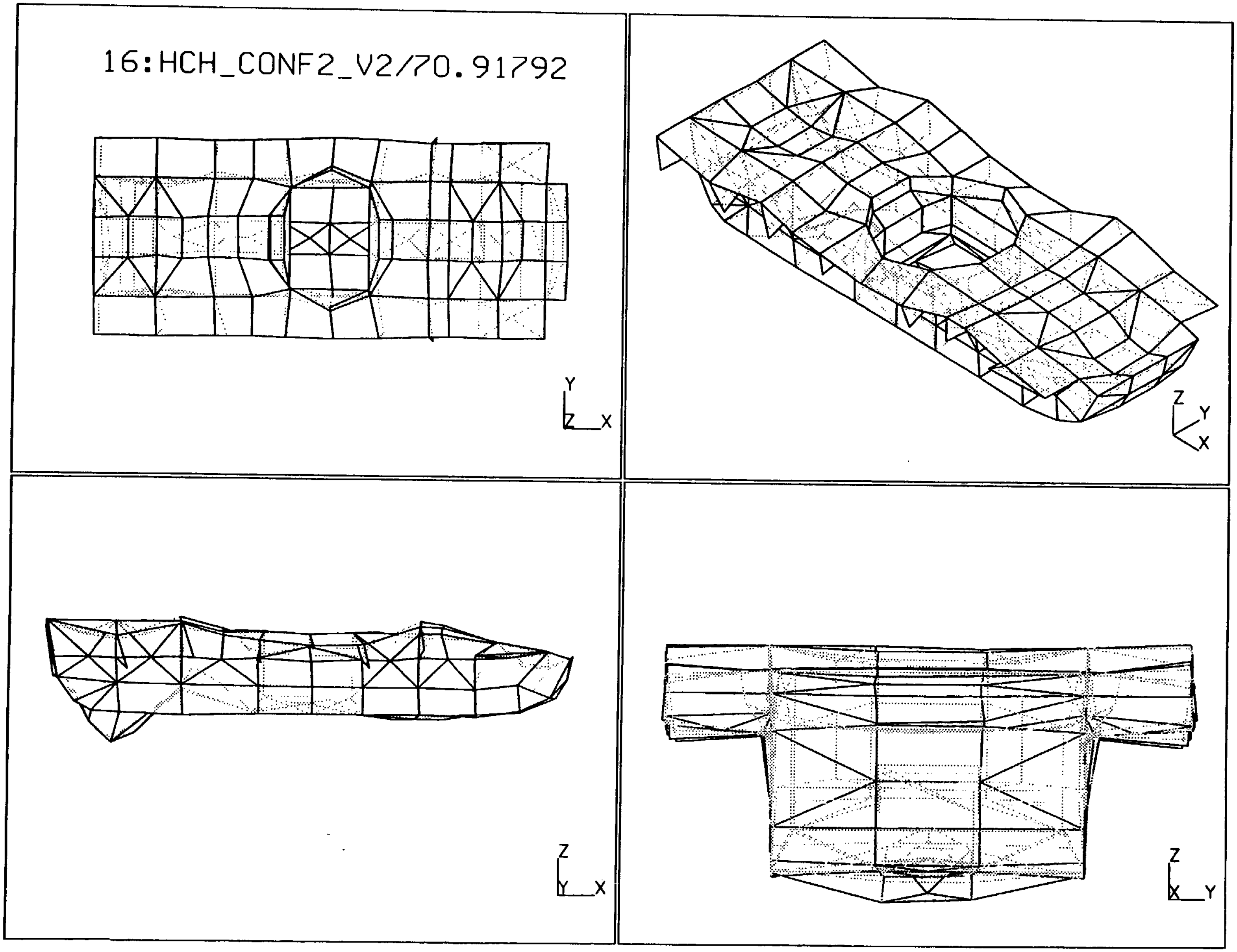

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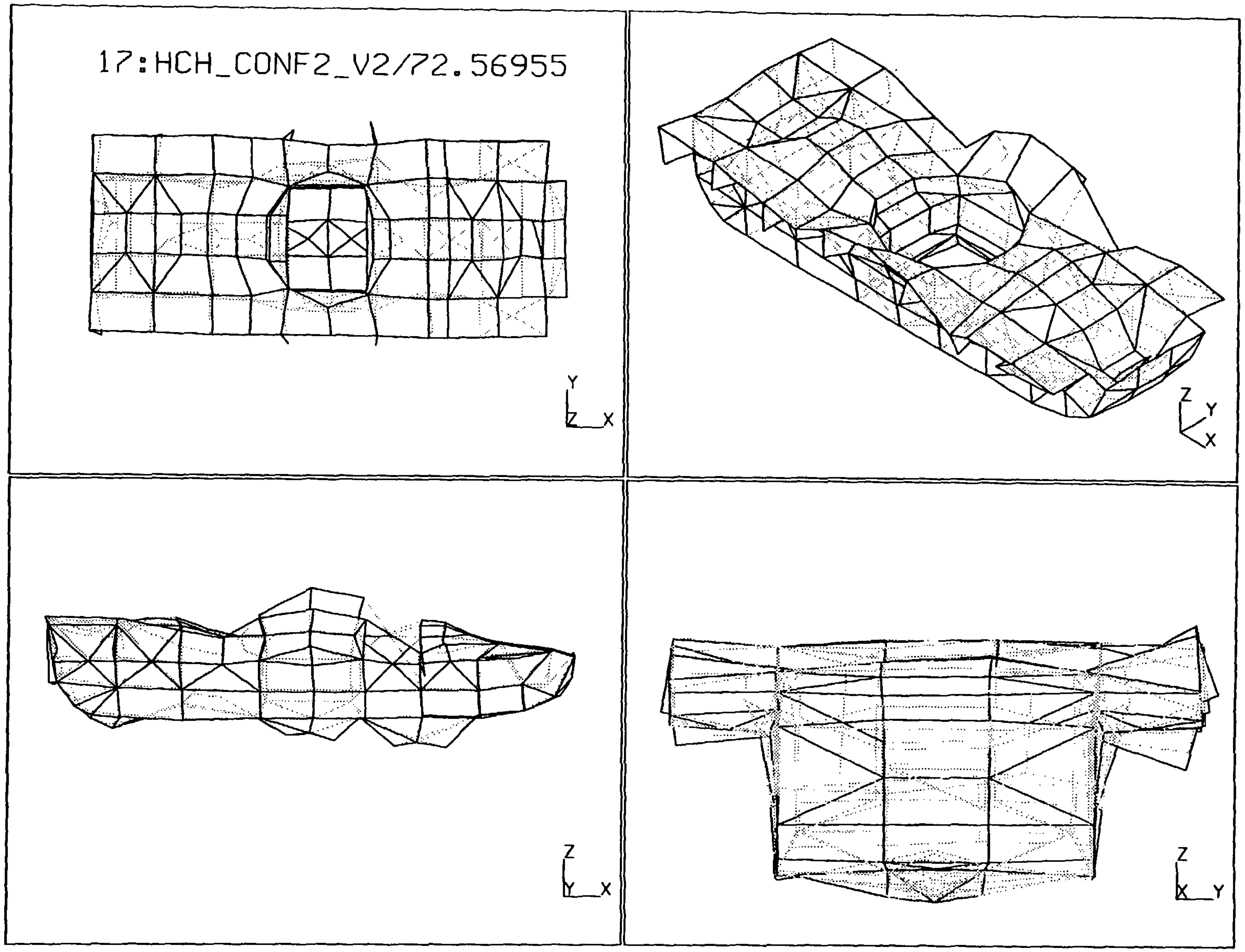

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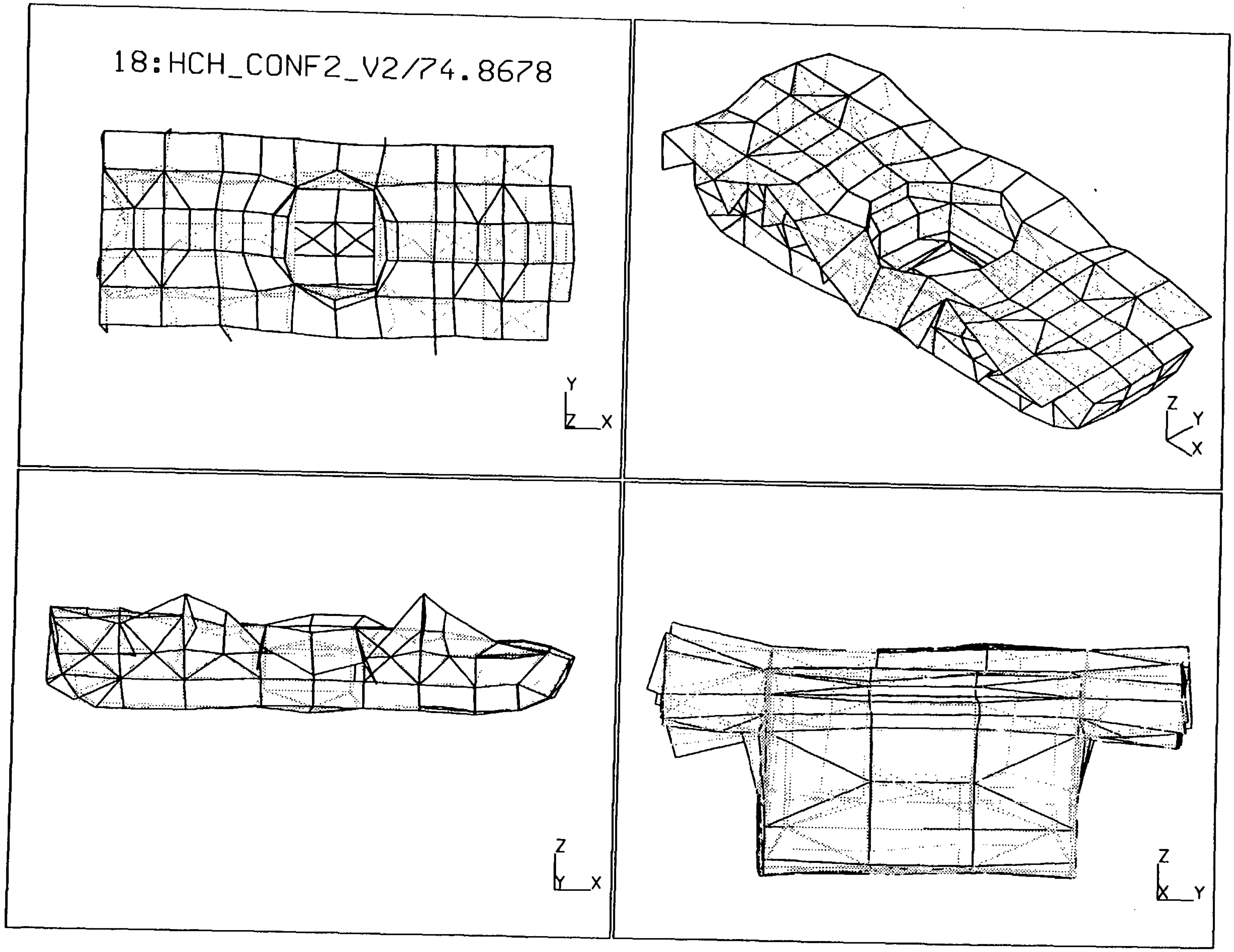

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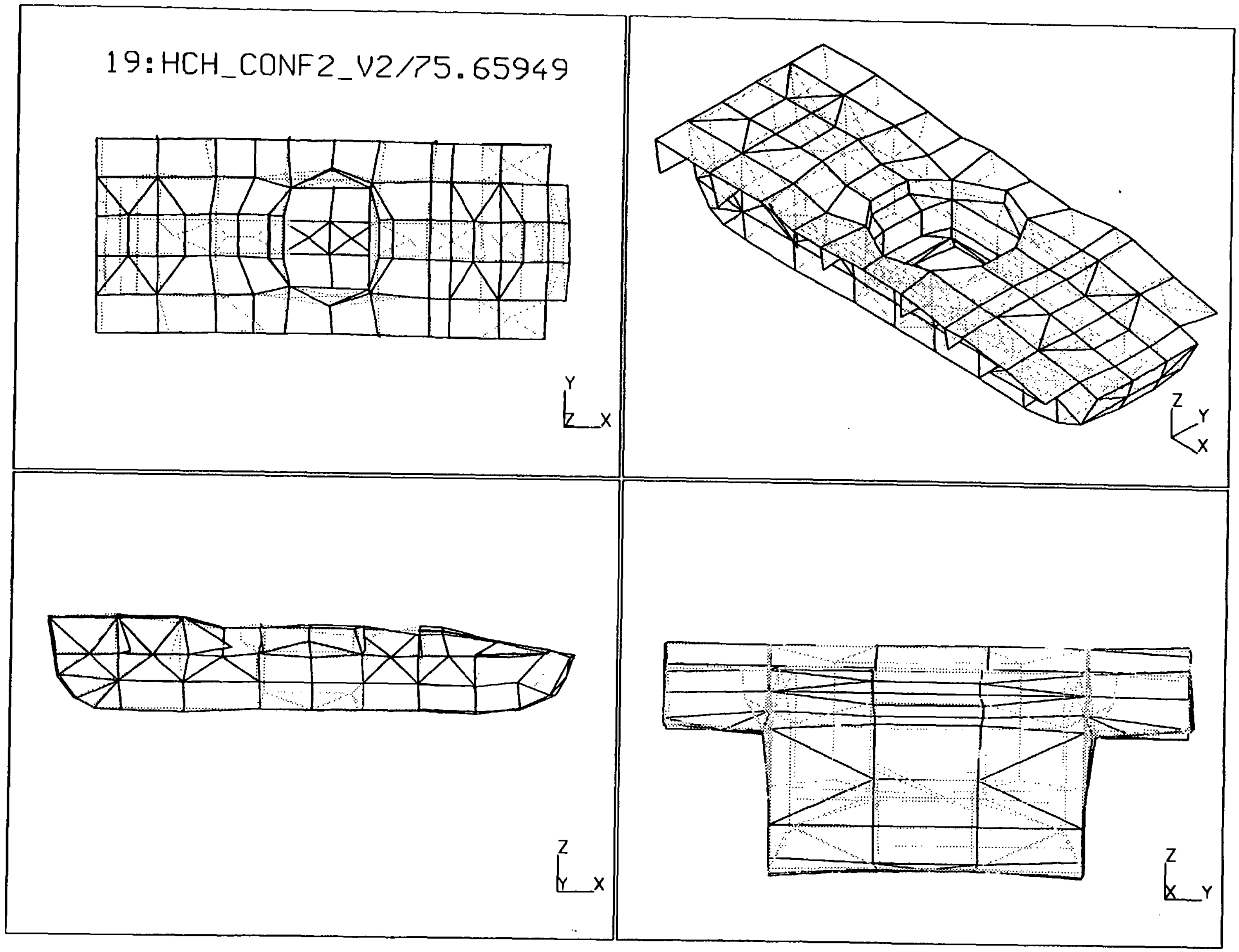

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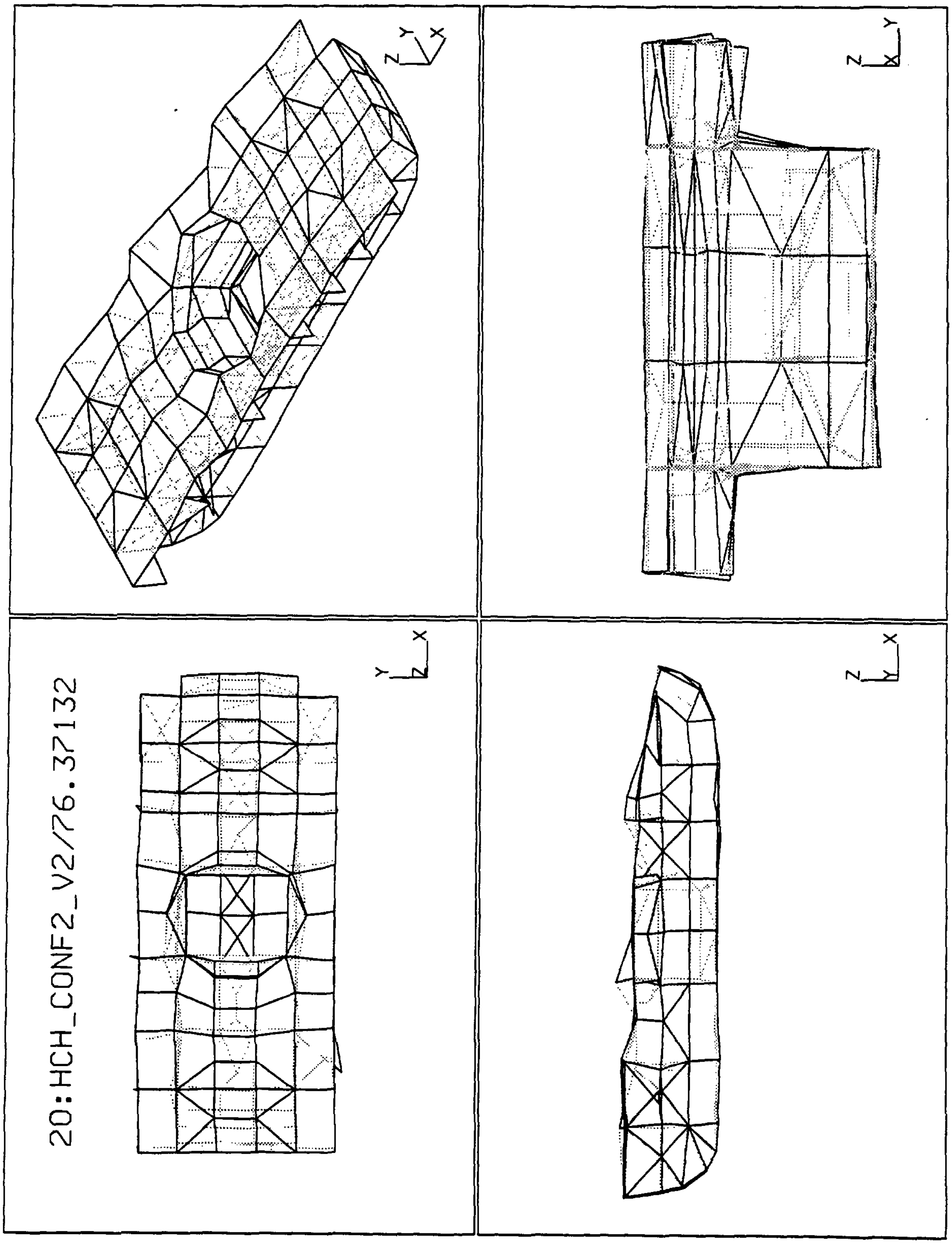

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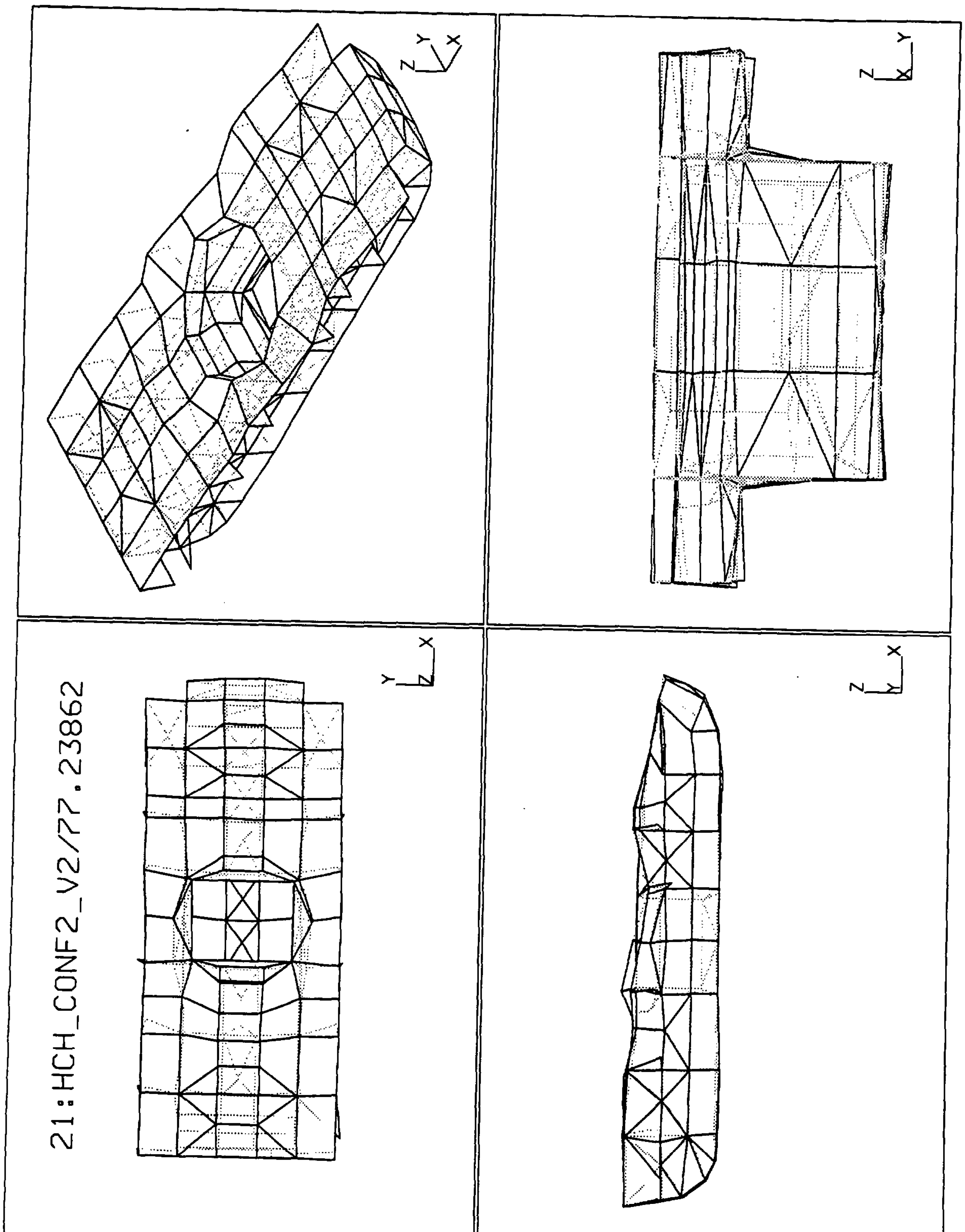

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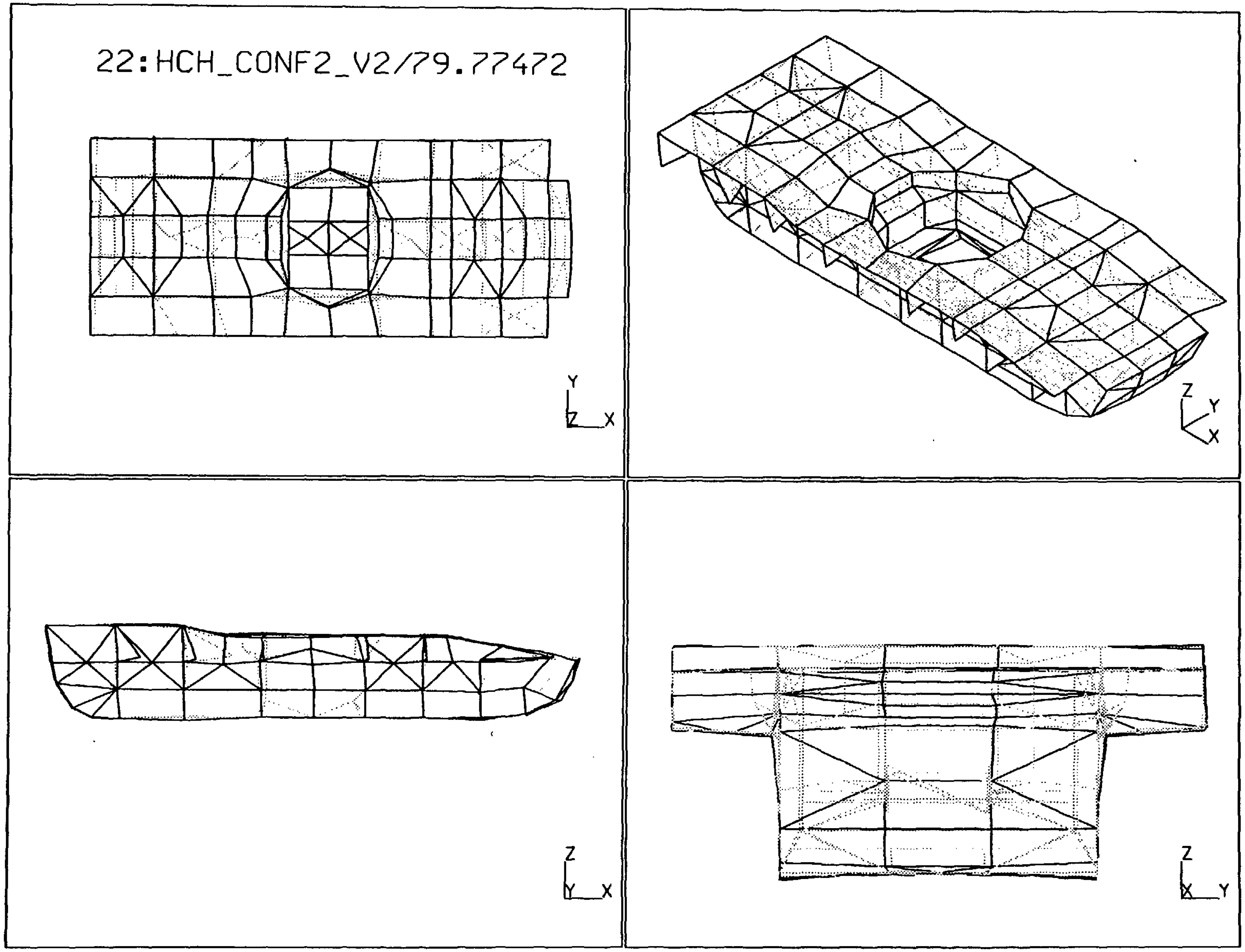

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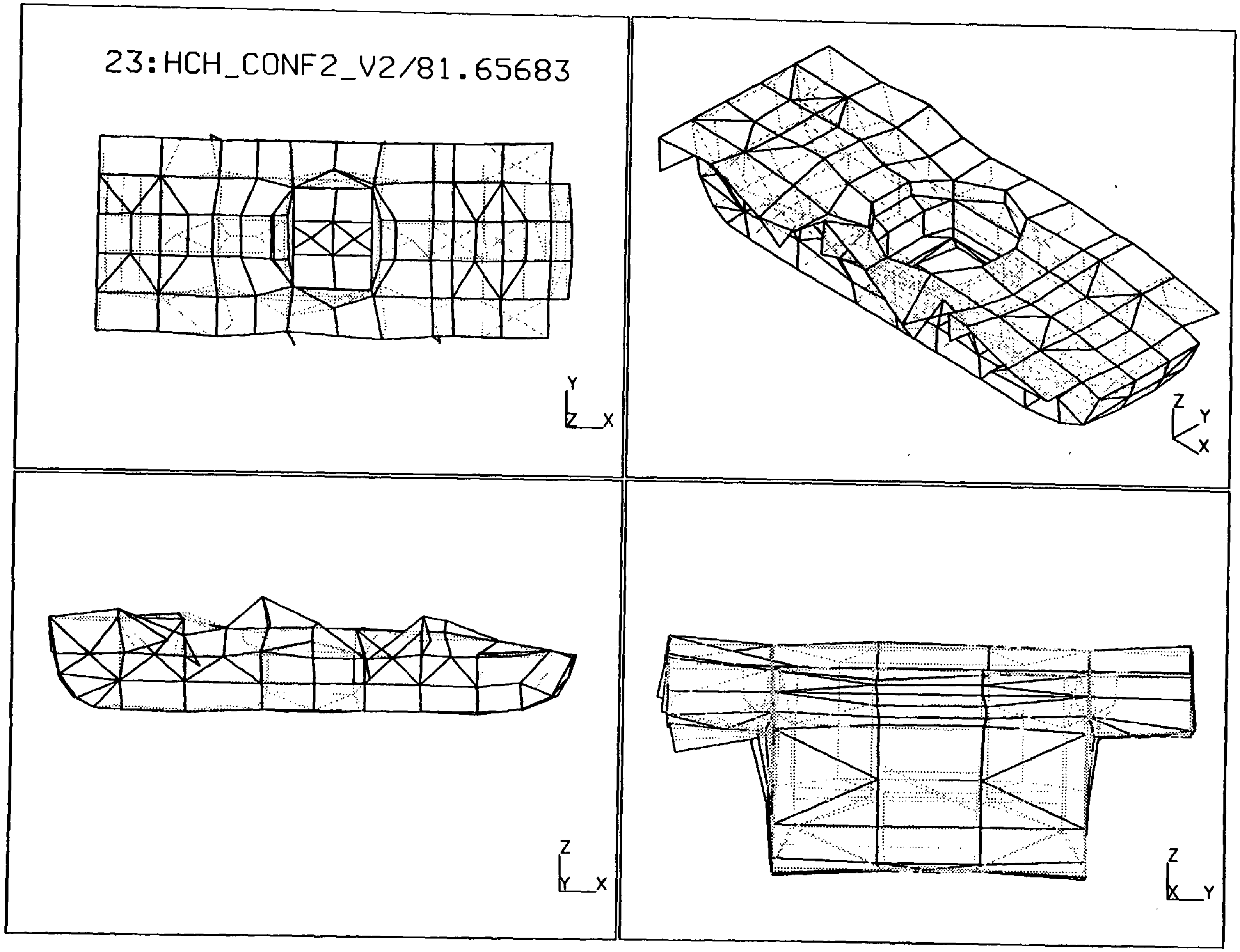

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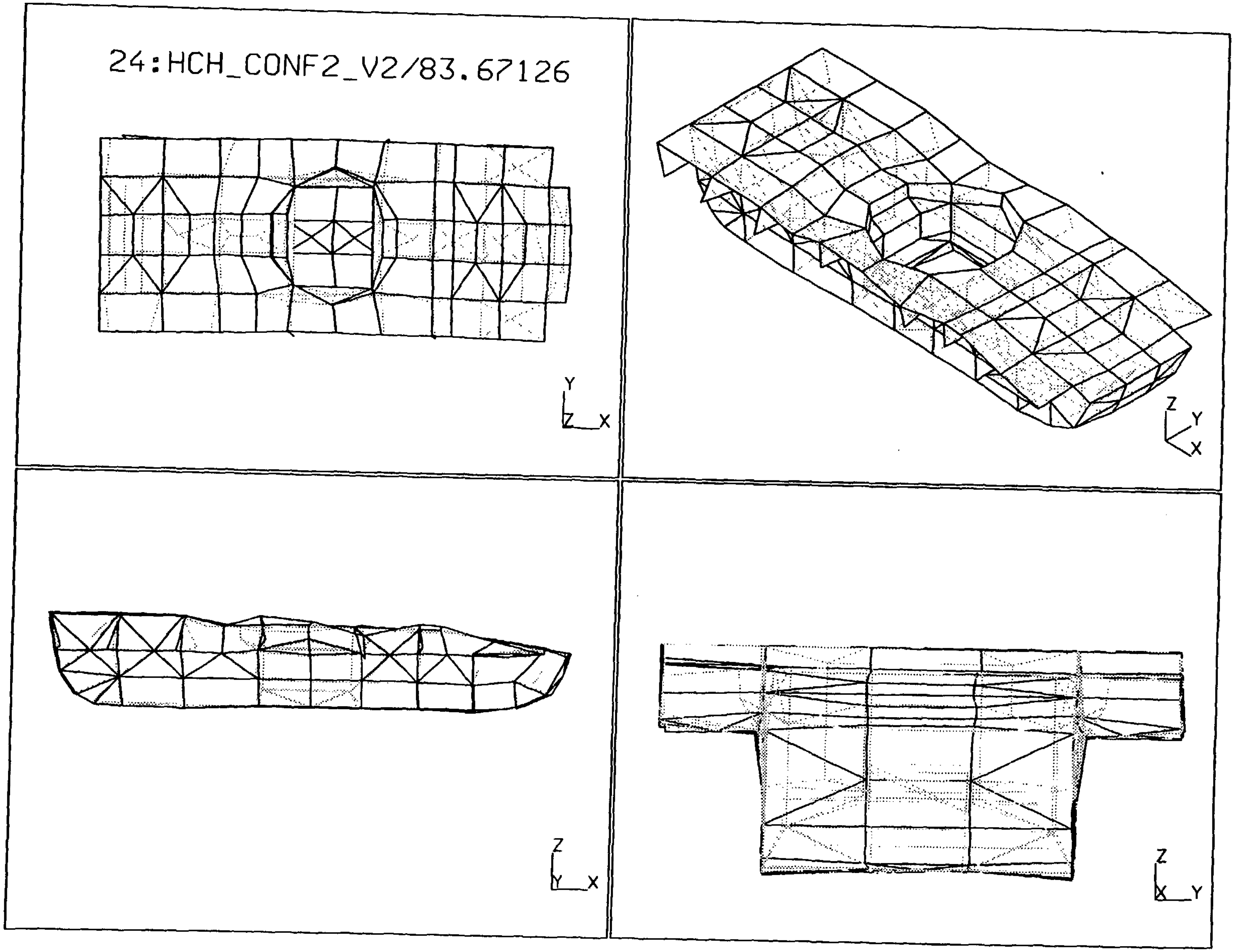

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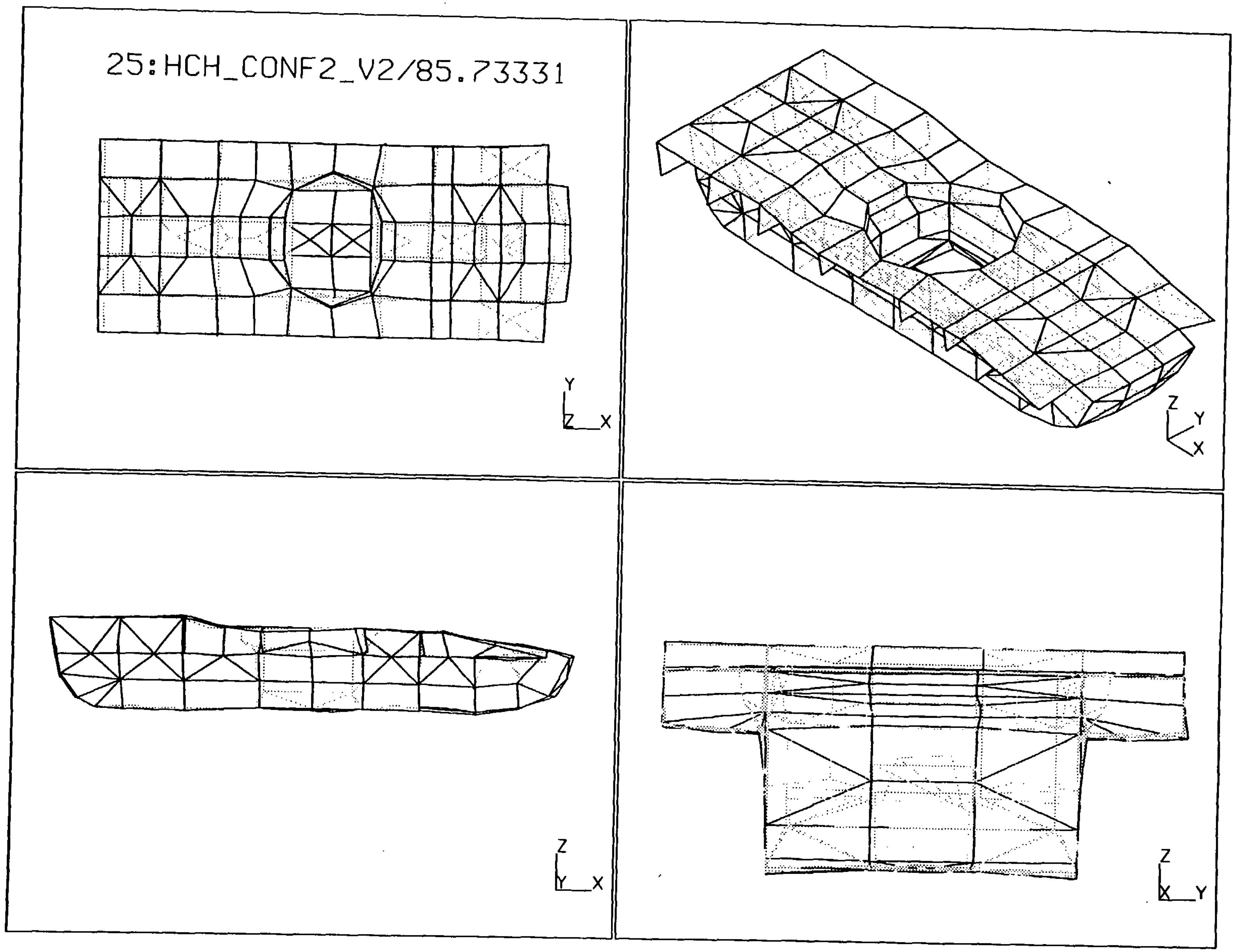

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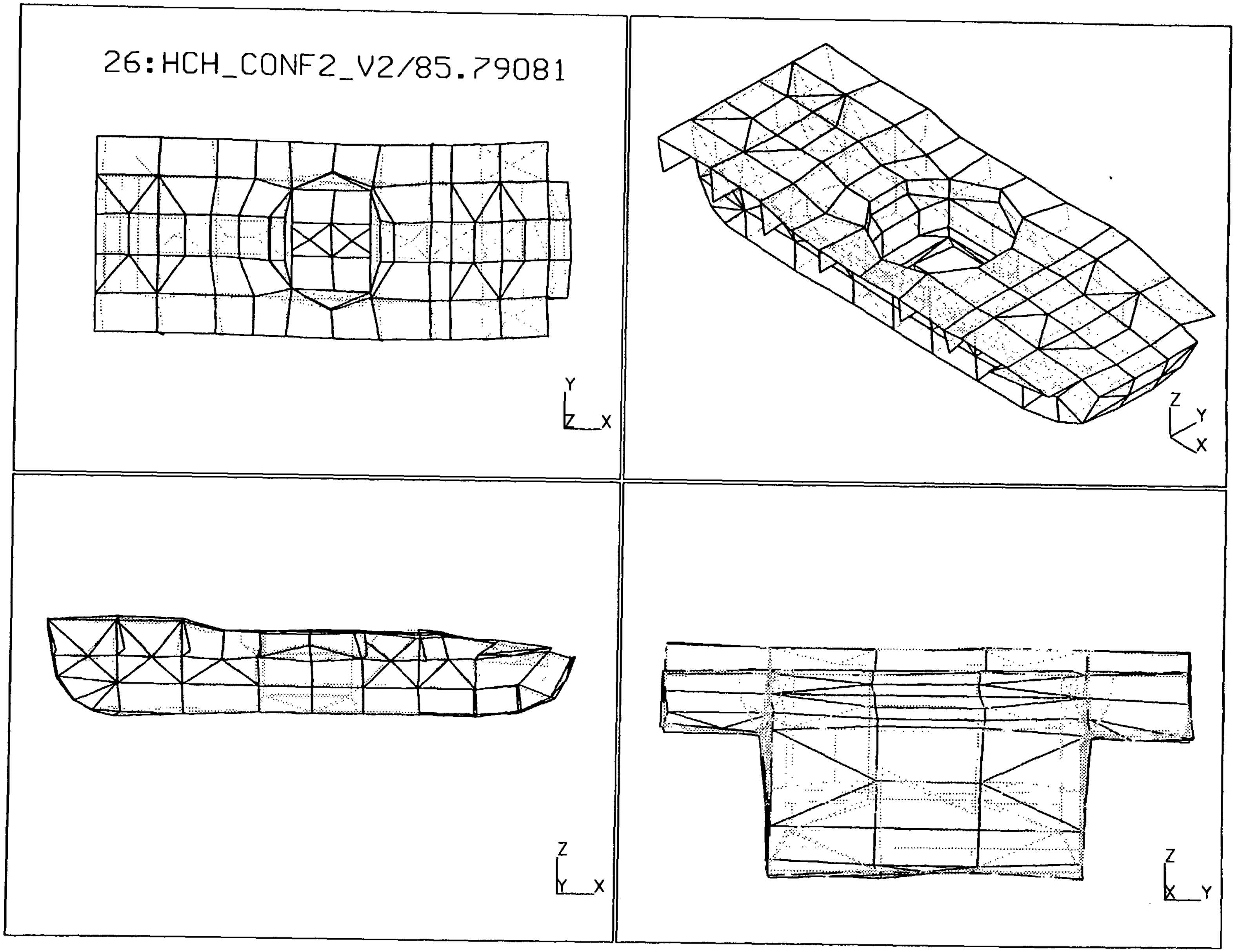

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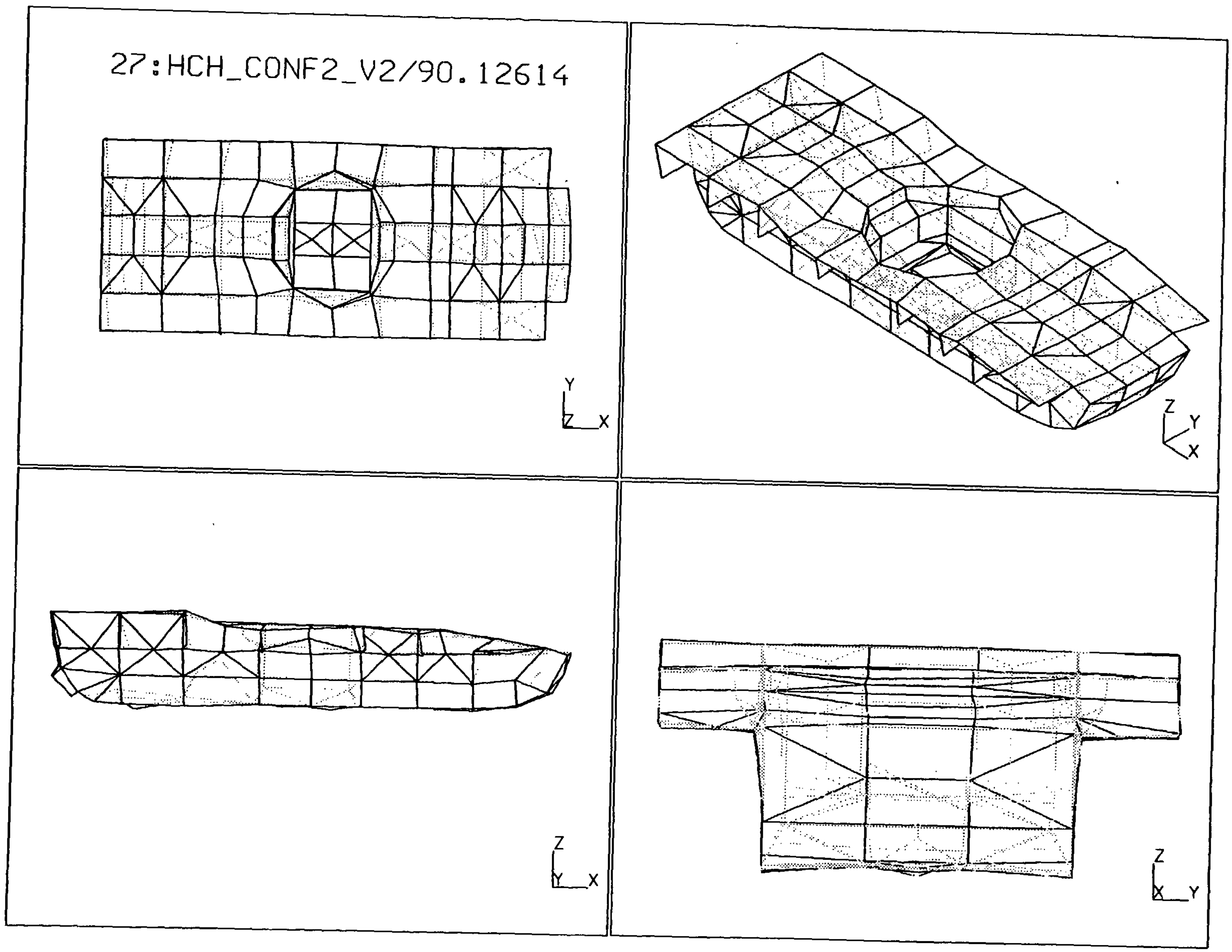

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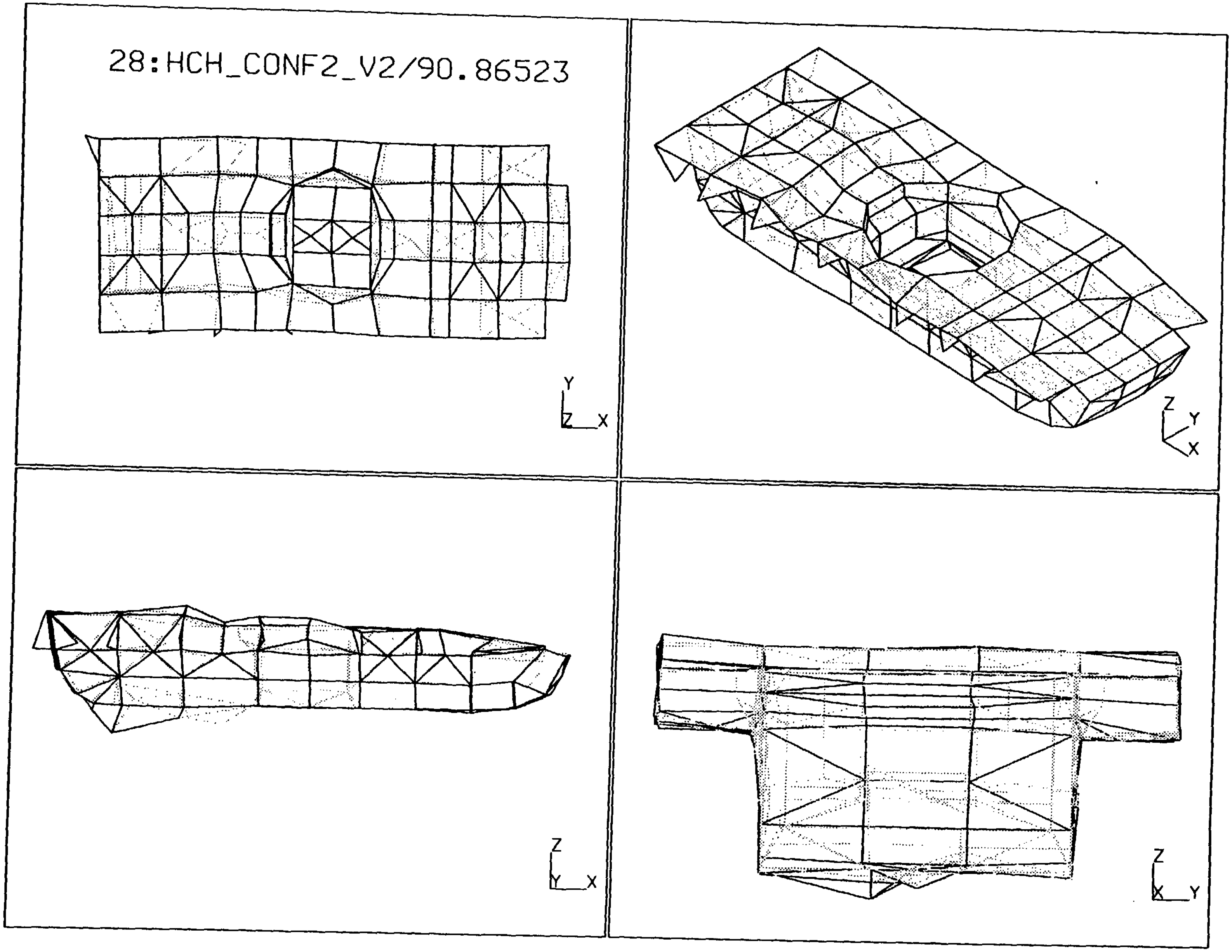

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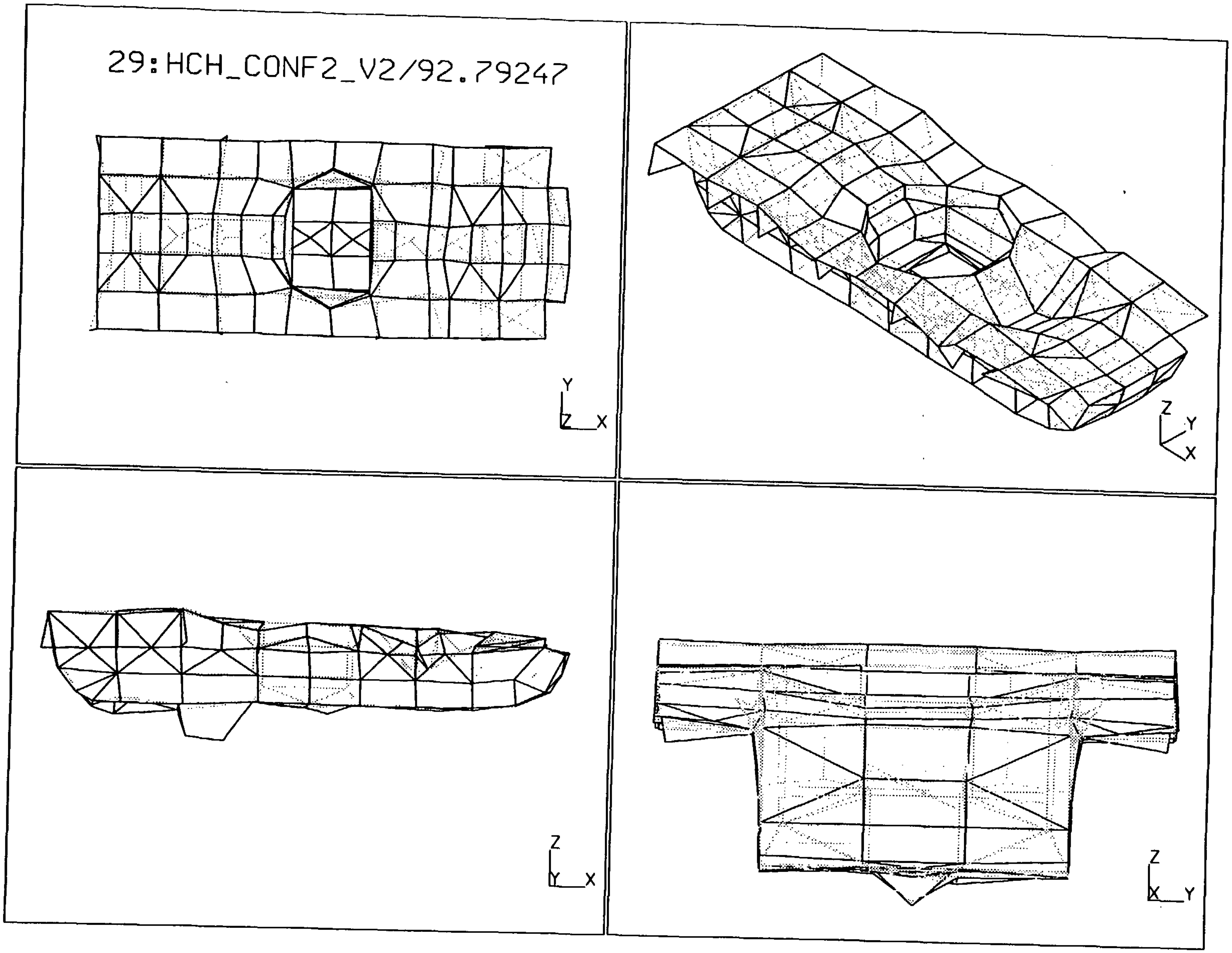

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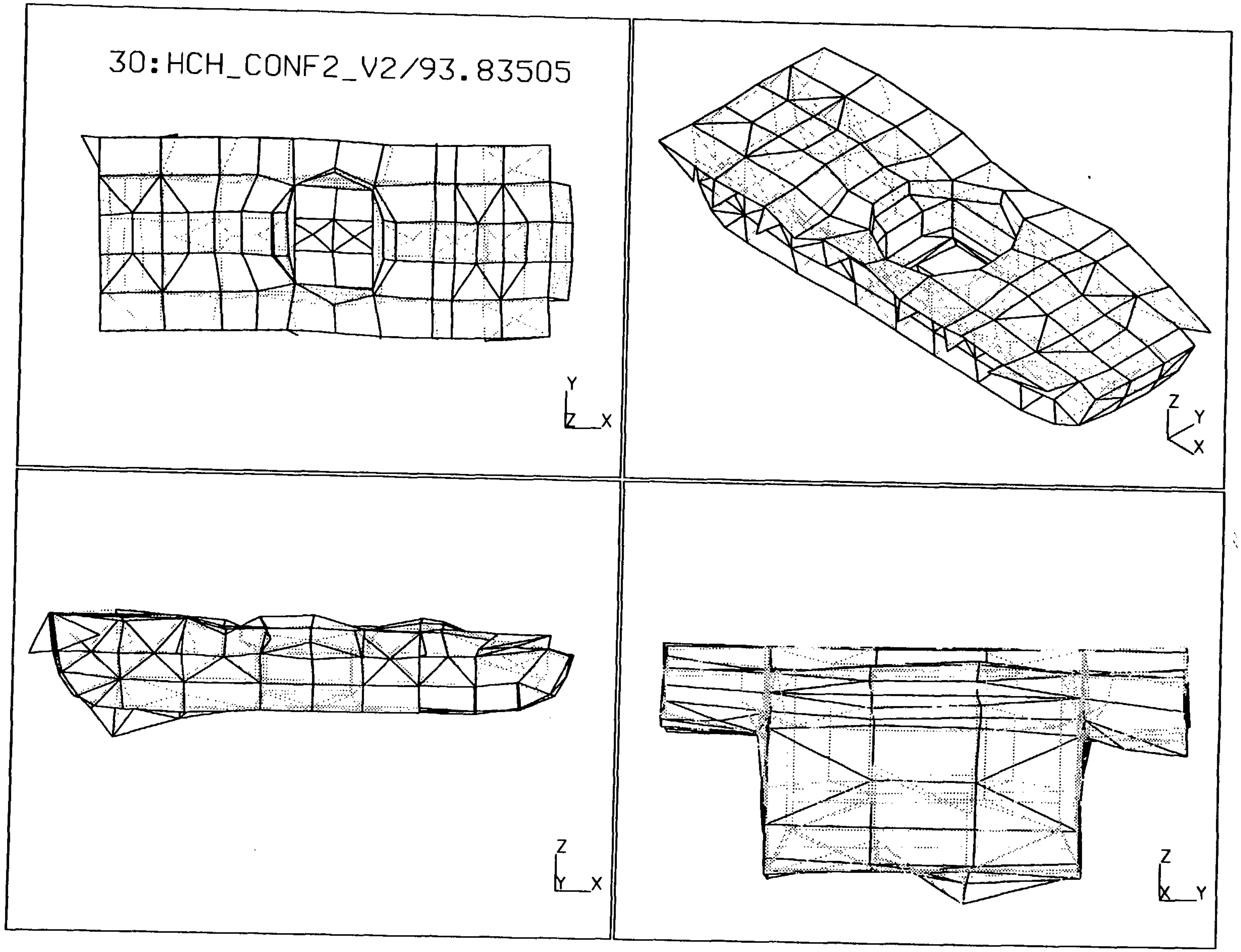

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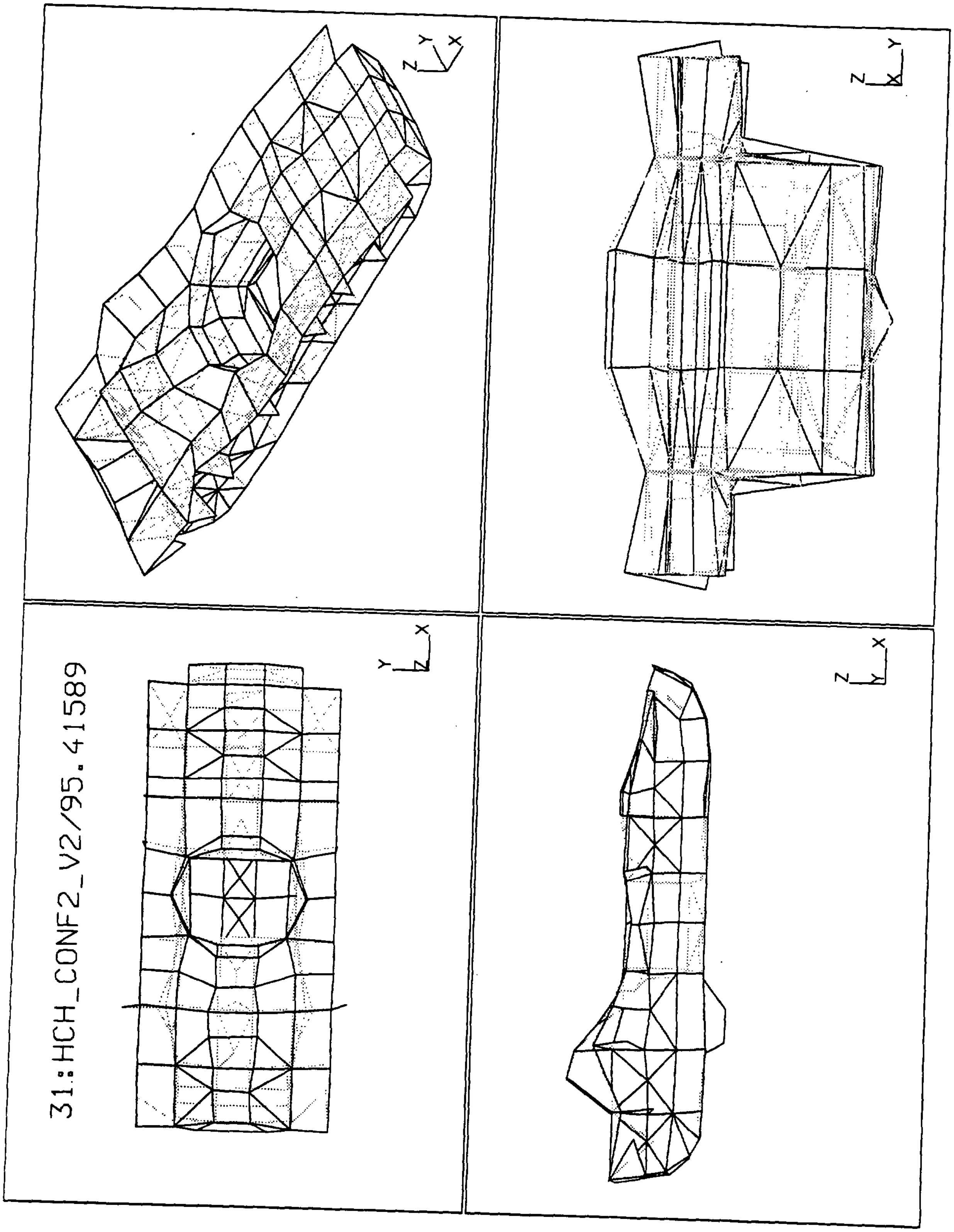

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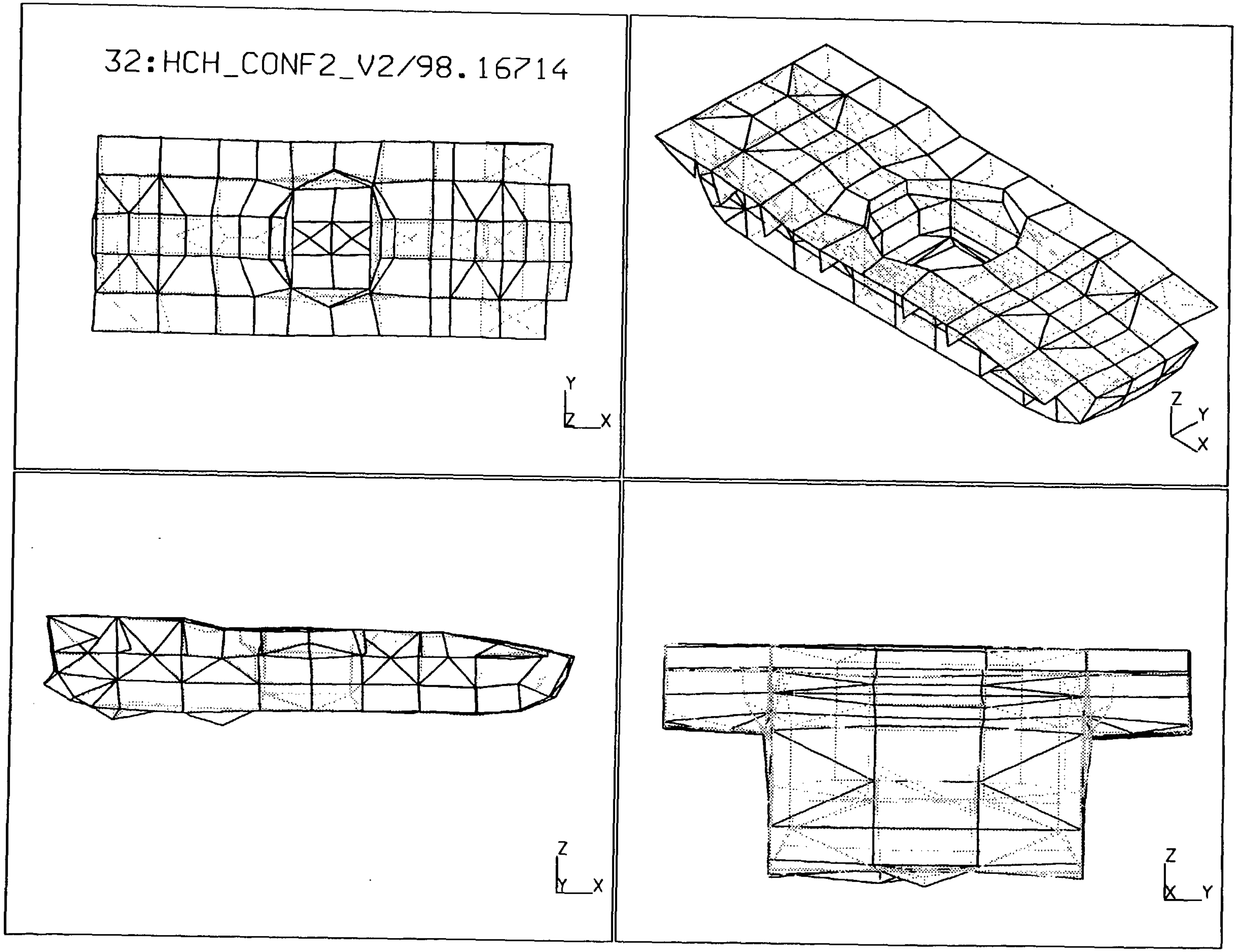

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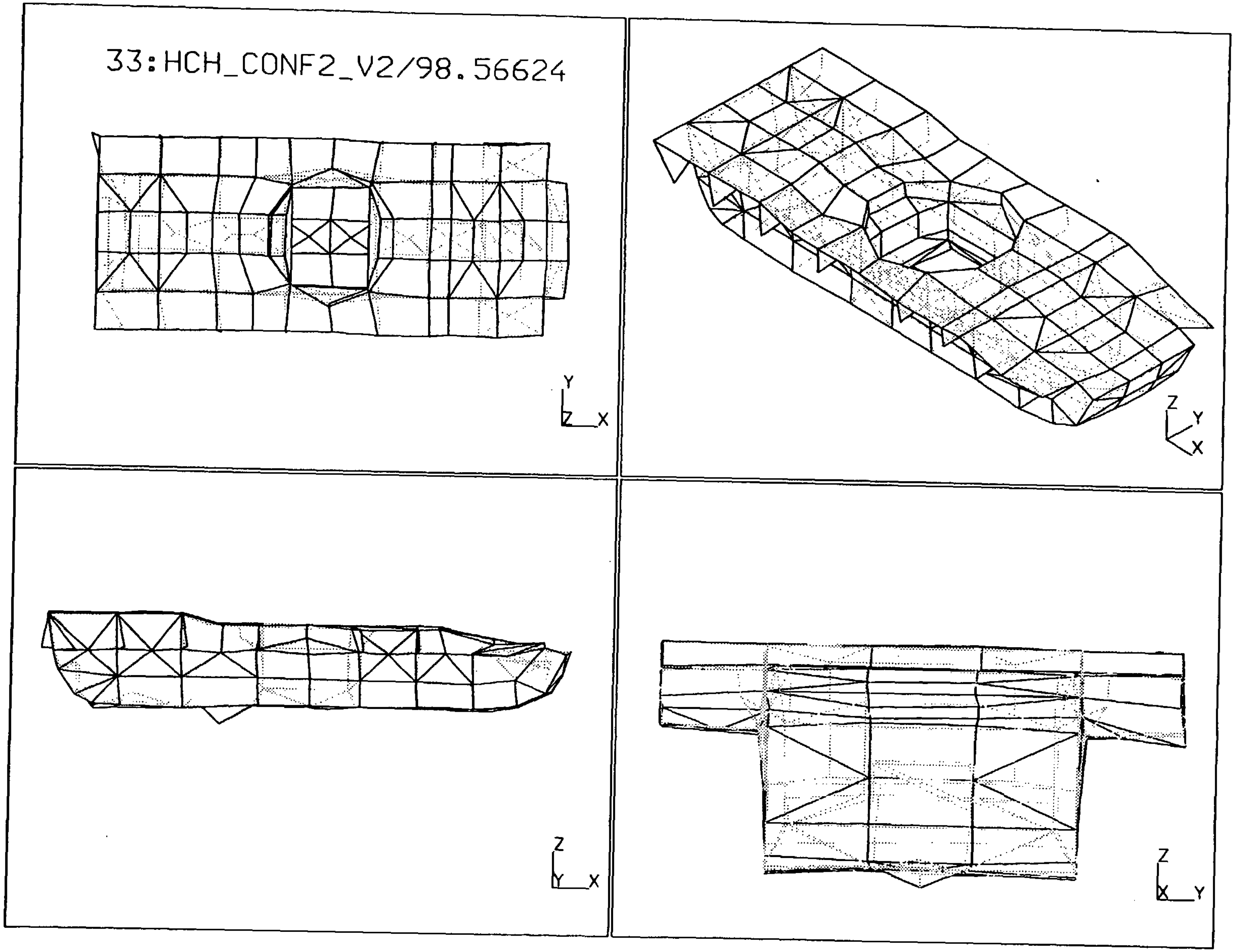

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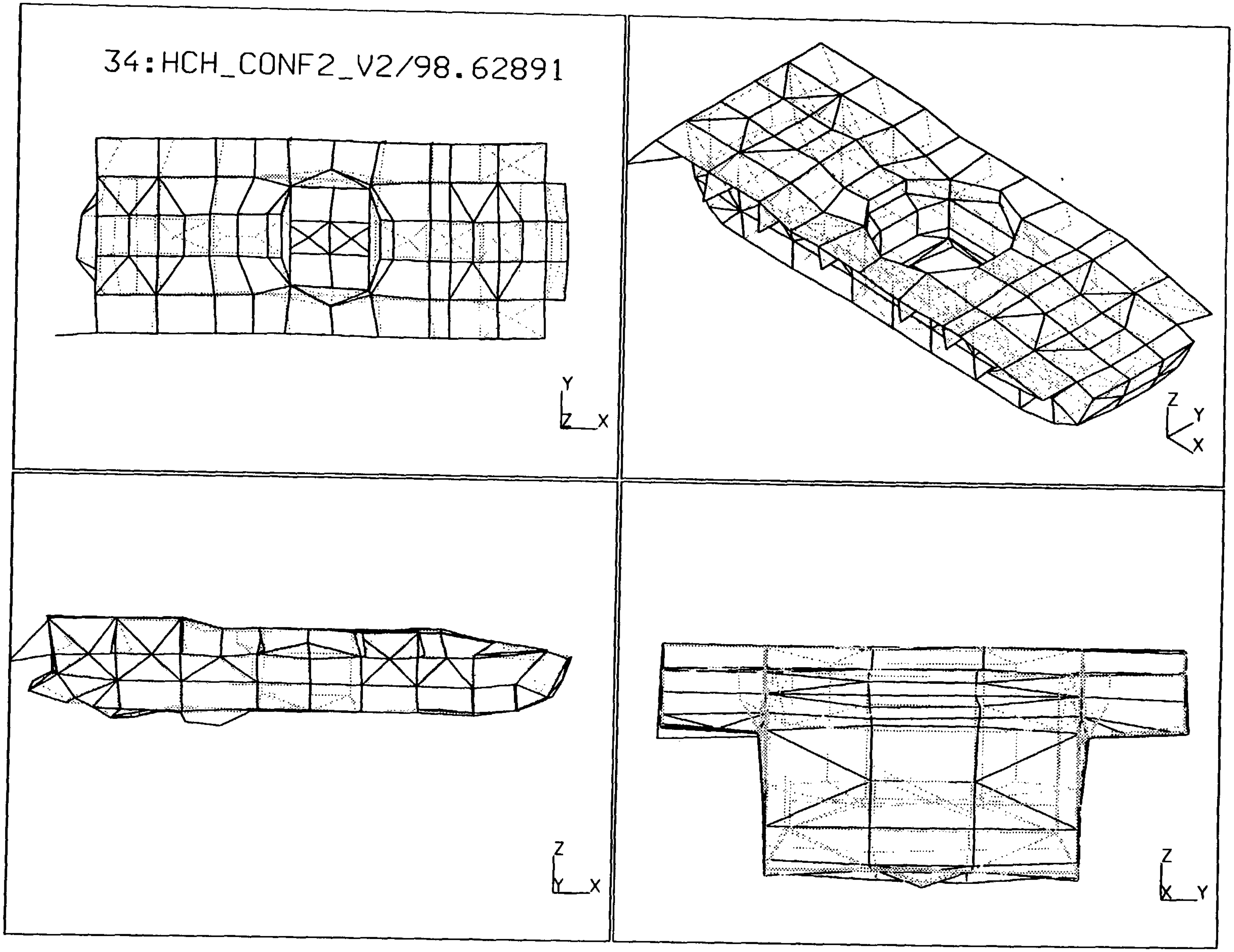

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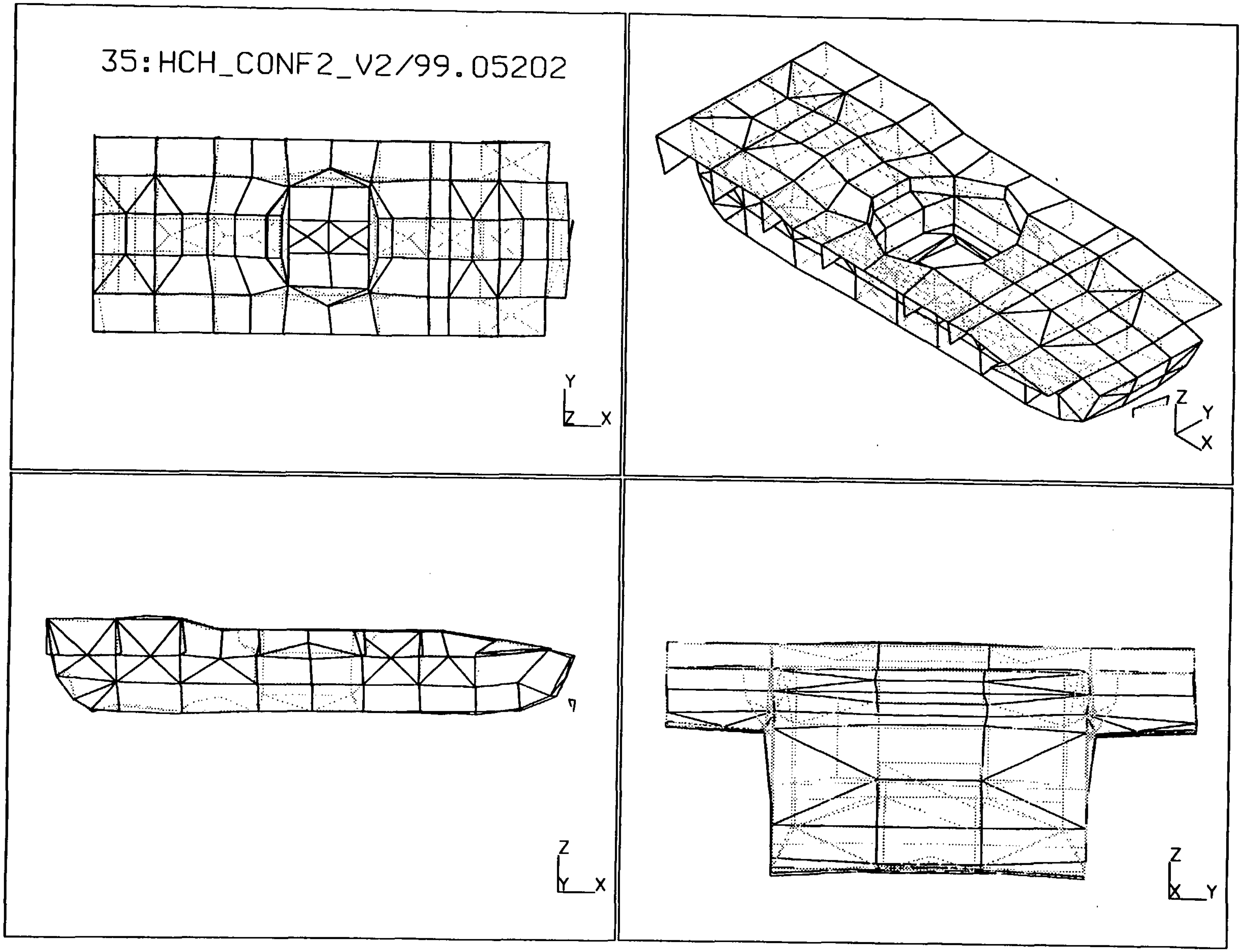

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13. ABSTRACT *(Maximum 200 words)*

A modal analysis was performed on the heavy composite hull (HCH). The object of this experiment was to provide structural dynamic information to be used to validate a finite element model. The experimental model was also used to update the finite element model, as well as to provide damping information.

This report details the analysis performed on the HCH in two configuration. The first configuration utilized excitation by four shakers placed at the corners of the floor. The second configuration also utilized four shakers, but two were placed on the roof in an attempt to excite local modes.

The first elastic mode of the HCH was observed at 36.1 Hz (0.425% critical damping). Modes up to 100 Hz were analyzed for this report. This report describes the characteristics of the extracted modes.

14. SUBJECT TERMS

modal analysis, vibration, structural dynamics

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